



Avdelningen för Mineralteknik

International overview and outlook on comminution technology

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Abstract

This report concerns international overview and outlook on comminution technology for effective production of mineral powders in order to improve the product quality and reduce the energy consumption. These involve new and improved grinding mills (roller mills, stirred media mills, vibration mills, centrifugal mills, jet mills, etc) and high performance classifiers (air classifiers and centrifuges) as well as their industrial applications. The possible utilisation of other assisted techniques like chemical, or microwave or ultrasonic energies to grinding processes has been also described. In addition, this report presents recent international work and outlook on modern methods for on-/in-line control/analysis, modelling and simulation for optimisation of grinding production.

Keywords:

Minerals, powder, comminution, grinding, mills, classification, classifier, grinding aids, microwave, ultrasound, centrifuge, control, modelling, simulation.

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1. Introduction

Comminution is a process whereby particulate materials are reduced from the coarse feed sizes to the fine product sizes required for downstream or end use (Russell, 1989; Kwade and Bernotat, 2002). The operations are found in different process industries such as cement, mineral, coal, pulp and paper, ceramics, agricultural products, fertiliser, food, pharmaceuticals, and paint/pigment materials. Grinding, especially for ultra-fine grinding, is an energy-intensive stage in the overall of the process to provide materials in the proper fine size range for the required properties of final product. It is notorious that higher energy consumption and inefficiency in grinding technology of various materials have long been regarded as a major area for recent developments. A major problem in grinding is the enormous amount of energy required for producing particles below micron-sizes. Conventional mills (mainly, tumbling ball mills) have been used for grinding for many years, but the basic problem in this application is that the power consumed by a conventional mill is limited by the centrifugation occurring at speeds above critical, and the grinding media size are not too small. The impact energy of each ball will otherwise be insignificant. A low speed and large grinding media in a tumbling mill generate mainly impact and abrasive stresses. When particle sizes are in the micron size range, these two forces do not work well. Comminution mill development is always aimed at lowering the energy consumption, increasing the throughput and having a mostly universal machine for the very different grinding problems. In order to meet these requirements, numerous mills have been developed and improved by institutes/universities and companies worldwide during recent years.

Besides developments of new mills for effective grinding, equipment for classification is important. It is useful to discharge the fines or separate the coarse particle in the comminution process in order to reduce the energy cost and avoids over-ground particles in the final product. The resultant particle size distribution of the product from the grinding system is also determined by the classification. It is well known that classification becomes increasingly difficult as the cut size is reduced, and particularly if the material has a low specific gravity or a high fraction of ultra-fines. A current trend towards fine and ultra-fine products with higher surface areas means that more exacting requirements are increasingly placed on the classification system. Considerable efforts have been made recently to utilise and develop new air classifiers (Braun, *et al.*, 2002; Adam, *et al.* 2001; Farahmand, *et al.*, 1997) and centrifuges (Muller, Komper and Kluge, 1993; Timmermann and Schönert, 1995; Wang, Forssberg and Axelsson, 1997) for classifying micron sized materials in comminution processes.

Also, the feasibility of the application of chemical, or thermal or ultrasonic energies to the grinding process has been a viable avenue of exploration and research. These possible assisted-technique has a significant impact on the improvement of the performance and the achievement of lower energy consumption in a comminution process. Chemicals or grinding aids used in grinding processes generally increase grinding energy efficiency, bring down the limit of grinding, prevent the agglomerates or aggregates of ground particles, avoid grinding media coating and improve the rheology of material flow as well (Mootheadath, *et al.*, 1992). Thermal stress fracture is generated in microwave energy assisted comminution (Wang, *et al.*, 2000; Kingman, *et al.*, 1999 and 1998; Gungör, *et al.*, 1998; Haque, 1998; Xia, *et al.*, 1997; Salsman, *et al.*, 1997; Florek, *et al.*, 1995; Walkiewicz, *et al.*, 1991 and 1988; Chen, *et*

al., 1984). The fractures are induced along the grain boundaries between the different minerals as a result of the difference in the absorption behaviours and the thermal expansion coefficients of the materials. Microwave energy can reduce the work index of the certain materials, which favours the subsequent grinding for efficient size reduction, mineral liberation and energy saving. Also, a better breakage behaviour of a grinding device like high pressure roller mill can be achieved with assistance of ultrasonic activation (Gaete-Garrston, et al., 2000). The active roller with a high-efficiency ultrasonic vibrator piezo-electrically driven was designed to obtain low energy consumption required in comminution.

In addition, control and optimisation of the particle production in grinding device and process has become significant in order to enable the desired quality to be produced and optimise the energy consumption required for grinding. One option is to install an on-line or in-line measurement system (i.e., particle size analysis) for continuous control of grinding circuit has (Greer, *et al.*, 1998; Puckhaber, *et al.*, 1998; Kalkert, 1999 and Schwechten, *et al.*, 2000). As known, grinding circuits are notoriously unstable and unwanted fluctuations in particle size, pulp density and volume flow rates can result in the inefficient use of grinding capacity and to poor extraction of valuable minerals. Another is to utilise a computer simulator with proper models for design, optimisation and analysis of a comminution device or process (Morrison, *et al.*, 2002; Herbst, *et al.*, 2000 and 2001). The main objective for use of a simulator in comminution is to reduce energy consumption without decreasing the throughput and operating efficiency.

In this report, recent international work for effective comminution technology will be overviewed. These areas involved 1) development and application of new mills, 2) improved and new classifiers, 3) other assisted methods (grinding aids, microwave and ultrasound) and 4) on-line control, modelling and simulation as well. In addition, the outlook on these areas is also presented.

2. Development and application of new mills

Using the comminution devices for mechanically stressing particle materials remain the most practical way to carry out industrial comminution for production of fine materials. Improvement in the energy efficiency and the ground product quantity should be directed towards the design of machines in addition to the process optimisation. The development and application of the new comminution systems has been recognised to be of paramount importance due to the inefficiency of conventional comminution devices like tumbling ball mills.

2.1 Roller mills

2.1.1 High pressure roller mill (HPRM)

The HPRM has been applied to the existing comminution flow sheets for some brittle materials such as cement, coal, limestone, diamond ore, etc. since the middle of the 1980's. Figure 1 shows the principle of this equipment, which is based on the so-called inter-particle comminution. It can achieve an efficient comminution in a particle bed stressed under a high pressure (for most cases: 50 to 200 MPa). This high-pressure particle-bed comminution is the result of scientific investigations into the breakage behaviour of brittle particles under different stress conditions. The

research was first carried out by tests with individual particles and later by testing the action of forces on particle collectives. A patent was granted to Professor Klaus Schönert, now TU Clausthal, Germany, on the comminution process distinguished by a single application of a pressure of more than 50 MPa on a bed of brittle particles. According to Schönert (1991), the process is executed with double rolls which are designed, fed and operated in such a way that a bed of particles is formed in the gap between the rolls and set under the pressure mentioned. In spite of the fact that the product is agglomerated which means that a dis-agglomerating step is needed, the total specific energy consumption of the comminution system is 20 to 50 % less compared to conventional ball mills. The double rolls used for the process are on the first glance similar in design to conventional crushing, compacting or briquetting rolls but differ considerably in details, particularly in view of the very high separating force. The well-known disadvantages of conventional crushing rolls, e.g. uneven wear and low capacity, are not valid for the high-pressure comminution. The process results in some specific effects, e.g., introduction of fissures and cleavages in the particles, "selective" grinding in mineral liberation and possibly advantages in the downstream process. The capacity of the rolls is proportional to the circumferential speed, width of rolls, as well as thickness and apparent densities of the agglomerates or flakes. Kellerwessel (1996) summarised the main advantages of the HPRM as follows:

- less specific energy consumption and consequently less wear in a downstream ball mill;
- increasing the capacity of existing plants with comparatively small investment;
- better liberation of valuable constituents;
- more intense attack of leach liquor; and
- comparatively low space requirements depending on the selected flow sheet.

Numerous works during the past decade (Kellerwessel 1996; Forssberg and Wang, 1996; Fuerstenau and De, 1995; Schönert, 1991 and 1988; Mayerhauser, 1990; Conroy and Wustner, 1986) have indicated that an introduction of the HPRM into a comminution system for a brittle material can result in a decrease of the overall energy consumption for a required fineness of the final product. A number of manufacturers in Germany have produced the HPRM machines. Therefore, various terms are in use of the HPRM, e.g. Roller Press or RP (KHD, Humboldt Wedag, AG), Ecoplex (Hosokawa Alpine AG), Polycom (Krupp Polysius AG) and high-compaction rolls (Maschinenfabrik Koppert GmbH).

It is known that a large proportion of particles pressed under high compressive loads revealing micro-fractures and other defects favour a subsequent grinding since their particle stability is strongly reduced. This advantage has been found particularly for fine and ultra-fine grinding of predominantly brittle mineral materials (Wang, *et al.*, 1999 and 1998; Fuerstenau, *et al.*, 1999; Van der Meer, *et al.*, 1997). It is known that a large proportion of particles pressed under high compressive loads revealing micro-fractures and other defects favour a subsequent grinding since their particle stability is strongly reduced. This advantage has been found particularly for fine and ultra-fine grinding of predominantly brittle mineral materials (Wang, *et al.*, 1999 and 1998; Fuerstenau, *et al.*, 1999).

Because the HPRM is more efficient at lower energy inputs and the ball mill is more efficient at higher energy inputs, the greatest potential for energy savings should come from using the two different comminution modes in tandem or in series as a hybrid

grinding circuit. A systematic study of energy efficiency of comminution (Fuerstenau, *et al.*, 1999) found that the energy consumed to achieve a reduction ratio of 30 using the hybrid HPRM with ball mill system was only about 70 % of that required by ball milling alone. An additional aspect of energy reduction with the hybrid system is utilisation of the benefits of particle weakening and the flaws and cracks created in particles during the particle-bed breakage under a high compression in the HPRM. Van der Meer and Schnabel (1997) also described some of the specific features of the roller press and the effect of roller press grinding on the energy consumption of the subsequent ball milling. Their results with various ores showed that a reduction in grindability by high pressure grinding rolls can be demonstrated both on lab- and pilot plant scale. Figure 2 shows the results from various ores from the lab-scale tests. The results confirmed the decrease in work index and indicated that this reduction in grindability increases with applied roller pressure.

Wang, Forssberg and Klymowsky (1998) investigated that the pre-grinding of filter cake limestone (12.6 % moisture) by the HPRM favoured a subsequent wet ultra-fine grinding in a stirred media Drais mill. The ultra-fine grinding of the materials pre-treated by the HPRM becomes more efficient since micro-cracks are introduced during the compressive processes. The results indicated that the introduction of the HPRM as a pre-grinder into a wet comminution flow sheet for production of a fine limestone product is suggested for energy saving and size reduction. As shown in Figure 3, the fineness of the ground product increases with the pass number of grinding through the HPRM. The specific energy consumed for the material ground in a subsequent wet stirred media mill is dependent on the pass number of pre-treatment in the HPRM. It was found that the internal stress relaxation of the particle after the high compressive loads has a significant effect on the subsequent wet ultra-fine comminution. Furthermore, in another work with a dry hybrid system of HPRM and agitated ball mill named SAM 7.5, a limestone pre-treated from the HPRM was dry ground in a subsequent dry SAM for different numbers of the passes (Wang, *et al.*, 1999). It is evident from the results that significantly less energy is required to comminute the powdered limestone by the hybrid HPRM with SAM grinding process compared to grinding in the SAM alone. The total energy requirement for the production of limestone fines is dramatically reduced with the use of energy for pre-grinding in the HPRM. The fine powder product with $d_{50} = 8 \mu\text{m}$ can be obtained at a total energy input of more than 110 kWh t^{-1} in the case of a comminution system without the HPRM. For the same fineness the total energy consumption of less than 25 kWh t^{-1} is needed in the case of pre-grinding in the HPRM. Correct partitioning of the comminution energy between the HPRM and the subsequent stirred media mill is necessary to maximum the energy utilisation in efficient milling.

It is known that multiple treatment of particles pressed through the RP is often required in practice. The KHD Humboldt Wedag recently introduced an improved version of the RP with splitter setting (see Figure 4). This machine can operate for multiple passes in one unit by varying the splitter setting. It has a specific application in the processing of an iron ore concentrate blend from a stockpile in USA (Klymowsky, 1997). This improvement eliminates the incomplete compressive action of the pressed particles along the edge of the machine. The re-circulating material from the edge was about 300 % of the iron ore treated.

Wear protection on the surface of the rollers has become a challenge to the industrial application of the RP. The KHD Humboldt Wedag AG early developed a welded hard-facing on the roller's surface. A recent effort is the studs lining. The hard-metal cylinder shaped studs are inserted into the surface of the rolls according to a certain pattern. In operation, the interstices between them fill up with compacted material forming an autogenous wear protection layer. The protruding studs are worn off with time at an extremely low rate. The studs lining, as a rule, allows > 8000 hours of operation without any maintenance.

The rapid introduction of the HPRM in various processing industries during last years proves the advantage of this new technology for brittle materials. Some problems have appeared with respect to design details and wear, but this is normal in establishing a new system. The application will be broadened in the future, especially in the area of ores and fine materials. According to Schönert (1991), many questions concerning the HPRM applications are still unanswered. The most important issues involve: a) the capacity in general and especially with fine feed; b) wear mechanisms and wear material; c) micro-crack formation; d) profiled roller surfaces, influences on capacity and wear; e) segmented roller liners; and f) influences on down-stream processes as flotation and leaching.

2.1.2 Poittemill

The structure of Poittemill produced by POITTEMILL INGENIERIE Group, France, is similar to that of the normal HPRM. One specific characteristic of this mill is, however, to utilise a pulsated high pressure grinding cylinder or roller (Figure 5), which may lead to the energy savings. The pulsation of the roller allows the feeding of cylinders and dis-agglomeration of compacted cake. The pulsated pressure grinding cylinder allows for energy saving of 30 %, as compared with a conventional milling system. A system of this mill combined with an air classifier has been commercially applied into industrial mineral powder processing. For instance, one of the industrial installations has been in the production of limestone powders in Nordkalk AB, Sweden. In addition, materials treated include alumina, clays, baryt, cement, sand and talc.

2.1.3 HOROMILL

The FCB Research Centre in France has designed a HOROMILL. This mill has already acquired its reputation in the cement market in 1994. The configuration with one idle roller within a cylindrical shell is shown in Figure 6. The shell is driven in rotation by a gear motor via a rim gear and a pinion. The grinding force is transmitted to the roller by hydraulic cylinders. Internals are provided to control the material circulation. The main operational features of this mill are to combine effects of centrifugal force and adequate internals and pass several times pass between the roller and the shell. Grinding is thus achieved in several steps. The conjugate concave and convex geometry of the grinding surfaces lead to angles of nip two or three times higher than in roll presses, which leads to a thicker ground layer and a more significant grinding work. In principle, the grinding zone is regularly fed, which ensures a maximum and stable nip of the material between the roll and the shell. From the mechanical viewpoint, this mill combines proven elements from the ball mill (cylindrical shell on hydrodynamic shoes, drive gear rim) and elements akin to the press (roller, bearings) but with much lower grinding pressure. Figure 7 shows the

HOROMILL grinding efficiency with different materials. A term of the substitution ratio in the figure was used evaluate the process efficiency in dry ball grinding in cement industry and the value of the ratio was fixed to 1.0 for all the P_{80} tested (Evrard and Cordonnier and Obry, 1997). It is clear that the HOROMILL is at least 1.5 times more efficient than an optimised dry ball mill. They reported that the main advantages are: a) larger capacity, b) good grinding efficiency, c) process flexibility and d) good preferential performance. At present, more than 9 machines have been in operation worldwide. Table 1 lists the main data associated with 3 machines in operation for treatment of different materials.

Table 1. Details for 3 HOROMILL machines in various commercial operations

Parameters		SMA, France	Karsdorf, Germany	Tepetzingo, Mexico
Mill size	mm	1600	3800	3800
Material ground		Anhydrite	Slag + clinker	Limestone + clay
Feed size	mm	<10	<50	< 100
Output	t/h	12	65	225
P_{80}	μm	18	25	65
Specific energy	kWh/t	11.0	25.4	6.5 to 8.0
Substitution ratio based on P_{80}		3.5	2.1	1.7 to 2.2

2.2 Stirred media mills

2.2.1 Sala Agitated Mill (SAM)

During recent years, a variety of agitated media mills have been developed and applied worldwide. One of those is the Sala Agitated Mill (SAM) which was developed by the formerly SALA International AB, Sweden, as shown in Figure 8. This type of mill is presently manufactured by Grinding Division of Metso Group in UK. It is designed for both wet and dry fine grinding. It has been reported that the SAM offers significant reductions in specific energy consumption compared to conventional grinding (Marmor, 1993). This reduction is mainly due to the application of small grinding media and the resultant high-energy intensities. On the other hand, the use of small grinding media provides an effective surface area enhancement in the final product. Those mills are lightweight and compact and require as little as 10 % of the floor space taken by a comparable tumbling ball mill.

In dry, fine grinding, an improvement of the grinding efficiency by the SAM may be considered mainly in terms of: a) efficient transfer of energy from grinding media to the material to be ground. It is well known that the shape and size of the media affect the grinding action between particles and media within the mill. b) use of chemicals as a grinding additive. A recent work (Forssberg and Wang, 1995) was aimed at investigating the effects of grinding media and grinding aids on fine milling of dolomite with a pilot scale SAM-7.5 in dry mode. The results showed that the grinding media plays an important role in the dry, fine grinding of dolomite in the mill. Replacing 8 mm ball by 8x8 mm cylpebs in the mill was found to be efficient for energy saving and size reduction. The smaller balls give a better energy utilisation due to the creation of the higher energy intensities compared to the larger size media. The beneficial effect of using amine as a grinding additive was significant for dry grinding

of the finer fractions. The actions of chemical additives in dry milling involve the elimination of aggregates formed and media and liner coating, the enhancement of grinding rate and improvement of the flowability of dry material. The dry fine grinding of a limestone with a small amount of quartz (feed size: 80 % <700 µm, Axel Gustavsson AB, Sweden) was another application for the SAM mill (Lidström, 1998). The type of mill was a SAM-30 in dry mode with a capacity of 4 t/h. The grinding media was 12 mm cypeds. The fineness of the ground product was 80 % <125 µm in which 50 % < 44 µm. The ground product was used to neutralise acidic lakes.

The SAM mill was also applied into re-grinding of a hydrocyclone underflow discharged in an industrial flow-sheet of separating gold at the Björkdal concentrator, Sweden (Lidström, 1998). The Björkdal concentrator processes approximately one million tons of gold ore per year. The ore contains approximately 3 g/t. gold. Gold is first recovered in a gravimetric circuit from the underflow fraction from the hydrocyclone. The overflow fraction is bypassed to the flotation circuit. The feed to the flotation circuit before the installation of the SAM mills contained coarse particles up to 600 µm and with 15-20 wt. % >250 µm. The gold in this feed was found to occur primarily in the coarser size fractions, which are difficult to recover by flotation. Further grinding of the feed by the SAM mills was needed. After regrinding with the SAM, the fraction > 250 µm in the feed material was reduced to 5 wt. % and the maximum size was only 400 µm. This feed size was found to be a suitable particle size for gold recovery.

2.2.2 IsaMill

The IsaMill, which was specially designed and developed by NETZSCH-Feinmahltechnik GmbH, Germany, has been used for very fine grinding of McArthur River and Mount Isa zinc/lead ores in Australia (Enderle, *et al*, 1997). This mill is a large horizontal stirred mill. The grinding media in the mills are oversize particles from screening in the primary semi-autogenous grinding circuit at McArthur River and the coarser particles after screening of slag and heavy medium plant reject streams at Mount Isa. These zinc/lead/silver deposits require a regrinding product of 80 % passing 7 microns to improve the liberation of non-sulphide gangue in particular and produce a single bulk zinc/lead concentrate. However, there was no accepted technology for economic production of such fine particles by regrinding in the base metal processing industry. The design of the large ISAMILL with the volume of 3000 litres and a 1.1 MW motor met this specific requirement. This mill can achieve high throughputs of solids up to 80 t/h and of pulp up to 140 m³/h. The results on size reduction and specific energy consumption as well as the operating condition with the ISAMILL 3000 litre volume are listed in Table 2, which also shows that a desired efficient energy utilisation was achieved at both sites.

Table 2. The results at Mount Isa and McArthur River sites with the ISAMILL of 3000 litres (Enderle et al., 1997)

Site	Mill Pressure, kPa	Solid, wt. %	Specific Energy, kWh/t	Size Reduct. Retio	Pulp flowrate, m ³ /h	Solid flowrate, t/h	Power draw, kW	Size, 80% Feed	pass, µm Product
<i>Mt Isa</i>	225	65	7,6	1,67	110	65	700	20	12
<i>McA River</i>									
Open circuit	300	20	28	3,75	90	20	710	30	8
Closed circuit	425	20	36	4,30	65	15	700	30	7

At the McArthur River site, 15 t/h. of solids is being reground in each mill from 30 μm to 7 μm at a specific energy consumption of 36 kWh/t. At the Mount Isa site, 65 t/h of solids is being reground in each mill from 20 μm to 12 μm at a specific energy consumption of 7.6 kWh/t. The mills have been used in production units since 1994 at Mount Isa and since 1995 at McArthur River. The volume of the largest IsaMill is 4000 litres.

2.2.3 ALPINE ATR Mill

The ALPINE ATR mill is also an agitated ball mill (see Figure 9), which has been developed by Hosokawa Alpine AG. The ATR mill is reported to be ideal for dry production of ultra-fine mineral powders below 10 μm . A fineness of up to 70-80 % < 2 μm with high specific surface area can be achieved. This mill is often selected to operate in a closed circuit with ALPINE fine classifiers. This vertical mill competes with conventional jet mills but can be advantageous both for iron-free grinding and if there is a requirement for the mineral to retain its foliated structure. The grinding action is based on shear forces resulting from agitation between the grinding bead and the product. A low rotor speed is used to prevent fluidisation. The feed material enters from above and the residence time of the material in the mill is regulated by adjusting the speed of metering screw at the mill discharge. The ATR system has a double-walled mill jacket to permit water-cooling. Typical applications for the ATR mills include mineral fillers (limestone, quartz and talc), frets and titanium dioxide.

2.2.4 ANI-Metprotech Stirred Vertical Mill

The development of large scale stirred vertical mills have been undertaken by Metprotech, Australia. The schematic of the ANI-Metprotech machine is shown in Figure 10. This mill has been applied for both fine (20-40 μm) and ultra-fine (< 20 μm) grinding. The feed slurry is pumped directly into the grinding chamber and there is no vertical flow of grinding media in the mill. The ANI-Metprotech mill therefore has a rapid grinding rate, which much reduces the circulating load and the number of cyclones and the sizes of the pumps. The grinding chamber, shaft and agitator arms are provided with a range of replaceable wear parts designed according to the application and location in the mill. Special ceramic-lined designs are available for process environments requiring an iron-free circuit. This mill is capable of delivering a much higher power input per unit volume, typically 100-150 kW/m³ versus 20-30 kW/m³ for tumbling or tower mills. It has been reported (Clifford, 1998) that the production of a very fine product in a reduced residence time allows successful fine grinding of high-volume, low value materials such as minerals. The ANI-Metprotech mill has been used in wet ultra-fine grinding for the recovery of refractory gold in Ammtec Pty Ltd, Western Australia (Corrans and Angove, 1991). A common cause of refractoriness is encapsulation of fine gold within the matrix of sulphide minerals. The size and location of the gold with the sulphide matrix determines to a very large degree the nature of the process required for its liberation and recovery. Submicroscopic gold can be liberated by destruction of the sulphide with processes based on the use of thermal, chemical or biological oxidation. If encapsulated gold is coarser in size, say 1 or 2 μm to 20 μm , the liberation by ultra-fine grinding in the Metprotech mill becomes possible. Sulphide encapsulated gold in the size range 5-20 μm can be economically recovered by use of the Metprotech mill. The use of this mill enhances the efficiency of pressure oxidation for recovery of gold particles.

2.2.5 MaxxMill

Existing stirred ball mills are commonly used in wet grinding of material below 200 μm . The design of these machines does not allow a larger feed particle size. A new MaxxMill, has been developed by Maschinenfabrik Gustav Eirich, Germany expands the application of stirred ball mills to a particle size of several millimetres (Sachweh, 1997). The product of this mill can be used as the input for a conventional stirred ball mill for further grinding. Figure 11 shows the general design of the MaxxMill. This mill consists mainly of a rotating drum, a stirrer and a stationary wall scraper with an integrated filling pipe. The stirrer is located eccentrically to the middle of the drum with the eccentricity. The grinding media like steel, glass or ceramic balls with sizes of 3 to 10 mm are filled up to 80 vol. %. The coarse material enters the machine through the pipe in the wall scraper together with the carrier fluid (air or water). The material will be mixed intensively with the balls, which have a pulverising effect on the product. The fine product will be sucked from the upper layer of the balls through the product outlet. The grinding media does not leave the mill because of their weight. However, for a high viscosity slurry a sieve is needed to retain the balls. The MaxxMill is most effective with feed particle size up to 5 mm. The product will be below 150-30 μm . The throughput ranges from 100 kg/h to 20 t/h depending on the mill size. This mill can be used in ceramic industry for milling of the hard components and in mineral industry for grinding of minerals like limestone and quartz.

2.2.6 KD Tower Mill

In order to achieve a high recovery of particles below 10 μm , Mori et al (1997) have modified a dry tower mill through redesigning the comminution cell and the shape and insides diameter of the classifying parts. Figure 12 shows the KD-1 tower mill and the modified versions KD-2 and KD-3. The KD-1 is similar to the conventional tower mill in which the comminution and classification operate in the same column. In this mill, the particles are mixed with the circulating airflow generated by the blower and transported to the cyclone. The KD-2 has been structured as the KD-1 in the grinding cell but its classification column has been enlarged to reduce the airflow rate. It was found, however, that the maximum particle size of the product remained the same as with the KD-1 due to air turbulence in the classification. In the latest version KD-3, the classification column was redesigned and the cell has been provided with a net to reduce the air turbulence. With this modified KD-3, the fine particles pass through the net into the cyclone while the coarse particles are settled at the bottom of the column. The grinding media was steel balls of 20 mm. Figure 13 shows the results with three KD mills for dry fine grinding of limestone. The efficiency of the KD tower mill depends on the shape and design of the machine. It is important to decrease the airflow rate and air turbulence in the column of the classification for a better fragmentation. The KD-3 gave a high recovery of particles below 10 μm .

2.2.7 Some aspects on developments of high-efficiency stirred media mills

a) Use of smallest grinding beads down to 0.10 mm for superfine particle production
One characteristic of stirred bead mills is to use the smallest beads down to 0.1 mm as a grinding media to effectively utilise the transmitted grinding energy in size reduction at high speeds. Recent theoretical studies by the University of

Braunschweig, Germany (1999) indicated that the transmitted grinding energy (E) is proportional to two basic values, i.e., the number of contacts (BZ) and the intensity of the contacts (BI):

$$E \propto BI \cdot BZ \quad (1)$$

$$BI \propto BI_{mk} = d_{mk}^2 \rho_{mk} v_t^2 \quad (2)$$

$$BZ \propto BZ_r = nt \left(\frac{x}{d_{mk}} \right)^2 \quad (3)$$

where d_{mk} is the bead size, ρ_{mk} is the density of bead, v_t is the speed, x is the initial particle size.

In Equation (3), the number of contacts, BZ , increases quadratically with ratio of the initial particle size to the grinding bead diameter. If the particle size of the product to be ground decreases, compensation can be made with correspondingly smaller grinding beads, such that the number of the contacts is still sufficient. Meanwhile, the intensity of impact of the grinding beads decreases proportionally to their mass. Limited compensation can be made for this effect through higher contact speeds. This means that the fineness that can be achieved is limited by the contact energy required to just fracture the particles and a sufficiently high number of contacts, which is primarily dependent on the grinding bead diameter.

McLaughlin (1999) pointed out that running a stirred media mill with beads that are too large raises both the unit cost of milling including energy consumption and the total cost of the equipment needed to produce the product. To remain in the most efficient portion of the cycle, it is suggested to use media that is only 200 times larger than the d_{50} of the finished product. For example, a stirred bead mill plant that mills a 6 μm particles to 0.2 μm particle size using 500 μm beads operates very inefficiently, required 15 times the amount of time required to mill with proper sized 100 μm media and 15 times the fixed capital investment of the finished product.

b) New designs for separation of grinding media from the ground product

To achieve the finer particle size, an effective approach is to utilise the smaller beads at high speeds. However, one problem for the most conventional stirred bead mills is unreliable separation of the smaller beads from the mixture. Draiswerke GmbH, Germany has recently developed a new design of a stirred bead mill DCP-Superflow[®] in order to successfully separate small grinding beads from ground slurry product (Stehr, 1998). As shown in Figure 14, a complete mixture of ground material and grinding media in the mill is centrifuged by the spinning rotor and assisted by baffles mounted on the inner rotor surface. Adjacent to the baffles are slotted openings in the rotor cylinder because of the difference in density and size, the beads is separated by centrifugal forces and returned through the slots to the inlet area of the outer annular mill chamber. With the fresh particulate material flowing into the mill, the beads are again carried downwards into the outer mill chamber. In this way, a defined internal re-circulation of the grinding beads through the outer and the subsequent inner mill chamber is ensured. Moreover, a new centrifugal bead mill ZR120, which has been introduced by Buhler AG, Switzerland (Buhler, 2000), allows trouble-free utilisation

of very small grinding media at a high re-circulation rate (Figure 15). The centrifugal operating principle of this mill offers significant advantages. Smaller grinding media, which maintain in the grinding chamber by means of centrifuge forces, allow the required product fineness to be obtained within a shorter time.

c) Application of additional force fields such as centrifugation and vibration

As mentioned above, the smaller grinding beads in ZR120 mill produce rather high-energy intensities by means of an intensive centrifugal force field at high rotational speed. It is apparent that the particles are efficiently fractured by both intensive attrition and compression. In this mill, the pressure from grinding media can be adjusted to achieve an optimal efficiency by variation of the centrifugal force and the flow force. This is performed by a control system with its torque control function. The pressure from grinding media, which can be flexibly selected, also allows the processing of products with a wide variety of rheological characteristics and the utilisation of the grinding media diameter in a range of 0.20 to 0.65 mm. The design of this mill operates with a high grinding capacity and a good efficiency of the grinding media. This results in a high productivity in terms of throughput and product quality.

Schollbach (1998 and 1999) investigated the influence of grinding bead size on wet comminution in stirred media mills with vibration assistance. His results indicated that grinding media < 2 mm are too small due to the cushioning effect of the overall grinding media charge, on the other hand, grinding media > 5 mm were found to be too large as they allowed only limited possibilities for contact between the ground material and the media. In wet comminution of a limestone below $100 \mu\text{m}$ ($d_{50}=22 \mu\text{m}$) by this vibration assisted mill, the economically viable range of grinding media diameters are 2.5 to 4 mm. With the beads of 2.5-4 mm used as grinding media, some favourable effects on comminution efficiency and the energy requirement can be achieved, especially in the initial stage of the grinding process.

2.3 Vibration mills

2.3.1 Eccentric vibrating mill (ESM)

Vibration mills have been applied for fine grinding and pulverisation of raw materials in various industries. Gock and Kurrer (1998) considered that conventional vibration tube mills appear economically inefficient, which are caused by insufficient ratio of tube volume to zero weight and the high power loss due to bearing loads. Also, a constructional limit was readily reached. In order to exceed this limit, Professor E. Gock at the Clausthal University of Technology, Germany introduced a new mechanical vibration concept for vibration mills. In co-operation with the Siebtechnik GmbH, one new type of vibration tube mill named "eccentric vibratory mill or ESM" has been developed and patented (Figure 16). Unlike conventional mills with circular vibrations, this new mill performs elliptical, circular and linear vibrations. The device is eccentric and the mass is balanced by means of a counter mass. The major technological advantage consists of amplitudes of vibration of up to 20 mm, leading to a high degree of loosening and thus to a decisive intensification of the impact forces among the grinding media. Some studies (Kurrer, 1986; Kurrer, Jeng and Gock, 1992) found that the impulse in the conventional vibration pipe mills mainly occurs in the form of a normal impact, i.e., the grinding media is predominantly subject to impact stress. The distribution of the normal impact over the grinding tube

lining is periodically and locally pronouncedly inhomogeneous. The friction impact is an order of magnitude smaller than the normal impact and has a maximum amount in the range of 0-90°. In the case of the eccentric vibratory mill, however, the main wear zone is the range of 0-180°. Since the mean rotational frequency is many times above that of conventional vibratory tube mills, the influence of the friction impact is much more important from a mechanical point of view. The position of the main wear zone is thus attributed to the summarised effect of relatively high normal and friction impacts. Since normal impact prevails in the range of 0°-60° due to the predominantly orthogonal position of the large major axis of the ellipse to the grinding tube lining, there is friction impact in the range of 60°-180°. This is because the large major axes of the ellipse are rather tangential to the grinding tube lining. The transportation effect is changed by the increase of the circumferential frequency of the grinding media filling as well as the high collision probability as a result of the amplitude modulation of the individual balls, together with the far higher mean free path of the balls. This effect contributes to a significant reduction of the energy consumption, compared to the conventional vibration mills. This new mill may replace the conventional vibration tube mills for an efficient comminution of brittle materials due to its superior characteristics such as the considerably higher amplitudes of vibration and the rejection of circular vibration. In addition, the mechanical-chemical processes for some materials are also another application of this new vibration mill. Some work (Kwade, *et al.*, 2002; Wang, *et al.*, 2002; Gock, *et al.*, 1998) have confirmed that advantage of this eccentric vibration mill versus a conventional vibration mill can include a compact and modular design, a better mixing effect, higher energy density and a lower specific energy requirement.

The results obtained in a recent work (Wang, *et al.*, 2002) have shown that this eccentric vibration mill is appropriate to an efficient mechanochemical treatment of a brittle material like limestone, due to its superior characteristics such as the considerably higher amplitudes of vibration and the rejection of circular vibration. The mechanochemical treatment of calcitic limestone leads to a progressive loss in crystallinity, which is much more intense along the basal planes {104}, {110} and {202} of the crystal structure. The increased surface energy of the solids, due to the structural distortion produced by impact and friction of the mobile parts of the ESM mill, induces a progressive agglomeration of the particles, which tend to minimise the exposed surface. Mechanochemical treatment of the calcitic limestone allows a significant lowering in reaction temperature in the thermal decomposition due to the distortion of the crystallite and lattice strain. The excess enthalpy content in the ground solids increases with an increase of energy input in the ESM. This intensive mechanical treatment produces a disordered phase whose decomposition is easier and takes place at lower and not well-defined temperatures. The main effect observed in mechanical activation is particle size reduction and crystal structure modification, constitutes a promising way for achieving control of the reactivity in the solid state and for the preparation of metastable phases with new and useful properties.

2.3.2 VibroKinetic Energy (VKE) Mill

VibroKinetic Energy (VKE) Mill, which was developed by Mr. Bruce H. Winn, is one of major developments in vibration mill utilising a tuned spring system to suspend the grinding chamber and the vibration motor energy source, as shown in Figure 17. This mill has been manufactured by Micro Grinding Systems, Inc., USA. The VKE mill consists of a lightweight horizontal grinding chamber, supported by radically

positioned, tuneable springs at each end of the chamber. The springs discharge harmonic and kinetic energy during each cycle of the periodic force generator and supplements the force applied to the grinding chamber by the force generator and thus reducing the overall energy required to grind. Material is continuously fed into the mill by a controlled feeder. Grinding media can be of some different types such as steel rods, ball and cylpebs, ceramic balls or cylpebs. Material ground to the desired size is fluidised by inert gas or air injection for removal from the mill, allowing the remaining over-sized particles to be fractured without the cushioning effect of fine particles. Coarse particles discharged through the end of the mill are recycled back to the feed hopper. This mill has been applied to various materials such as pigments, bentonite, feldspar, zircon, barite, quartz, manganese, alumina, magnetite, precious metal ores, etc..

A comparative study with the VKE mill and the conventional Palla vibration mill has been performed in the treatment of a granite rock chips (Microgrinding Systems Inc., 1991). In their statement, the VibroKinetic Energy mill is almost twice as efficient as the Palla mill at the same conditions. Utilisation and/or substitution of the VKE mill in appropriate mill results in reducing power costs by almost half. They found that the production rate of the VKE mill is superior to the Palla mill.

2.4 Centrifugal mills

2.4.1 ZRM centrifugal tube mill

Gock, *et al.* (2001) developed a new model ZRM 220-35 centrifugal tube media mill for wet comminution of particle size below 2 μm . Figure 18 shows the design diagram of this centrifugal tube mill: The machine is a two-tube mill driven with synchronous motors via eccentrically mounted shafts. It runs in continuous operation, the suspension product is discharged radially via a discharge chamber. This mill can be used for wet milling of pigments, mineral filler, ceramic materials and chemical product. Unlike the common agitated ball mills, this mill has no fixed installations. Therefore, it is assumed wear can be drastically reduced. Figure 19 shows the particle size distribution of ground limestone product when limestone feed below 110 μm was ground. The specific energy requirement was 141 kWh/t for the product fineness of $d_{50}=1.8 \mu\text{m}$ at a single run. However, the present industrial production using the conventional agitated ball mills required approximately 150 kWh/t for the same product fineness at multi-runs.

2.4.2 Aachen centrifugal mill

A new centrifuge ball mill was developed for micro-fine comminution by Aachen University of Technology, Germany (Wellenkamp, 1997). The sketch of this mill is shown in Figure 20. The energy is transferred to the ball charge by means of a rotor. This is comprised of four wings, which divide the milling chamber into four quadrants. The rotor is powered by an electric motor controlled by a frequency converter, whereby rotations of 200 rpm to 1100 rpm are possible. The mill consists basically of a cylindrical milling chamber inside of which the rotor revolves. The chamber is double-walled in structure to enable cooling. In contrast to ball mills in which the ball are already centrifuged at a centrifugal acceleration of 1 G this new mill requires an acceleration of 6 G. This new mill has a potential for application in ultra-fine grinding in the future.

2.5 Jet mills

Besides, a recent development in fine and ultrafine jet mill grinding/pulverising has been made by PMT Zyklontercnik GmbH, Austria (Thaler, 2000). As known, jet mills are comminution aggregates, where expanding gases with high velocities, up to 1200 m/s, are used to comminute particles by impact with other particles (opposed jetmill), or built in targets (impact jetmill), or just by utilising high velocity differences (spiral jetmill). The PMT Zyklontercnik GmbH modified and developed their spiral jetmill PMT system for effective production of industrial mineral powders (Figure 21). A new and required part of this jetmill with the enlarged milling area is a classifier rotor, which is built in the mill with a centric or eccentric vertical axis with the advantage of maintenance-free and high-speed bearings. Together with the basic structure of the new rotor unit made from high strength aluminium alloy, the highest circumferential speeds of up to 160 m/s are possible. This high speed combined with the new form of the rotor leads to the lowest possible final product particle sizes with a $d_{50} < 0.5 \mu\text{m}$. Also, the milling body is different to commonly used jetmills, which are designed to keep the space inside as small as possible to prevent the product from escaping from the milling process. The PMT also replaced the injector with other feeding system to modify this spiral jetmill. Without the injectors, the specific energy consumption decreased by at least 20 %. This design is also simple to verify because the grinding inside the spiral jetmill is conducted essentially by high velocity differences. If the material is fed into the chamber with a higher speed, the velocity differences are very little and the grinding effect is also lower. When the particles are conveyed into the grinding chamber at a lower speed, the highest velocity difference between the particles and the high-speed air stream can be achieved. This means the whole energy from the compressed air can be utilised for grinding and not for feeding the material. Figure 22 shows the particle size distributions of the ground barytes, zeolite and graphite products by the developed PMT spiral jetmill. It was reported that this developed jetmills offers the following advantages: a) exact top cut; b) reduction of the specific energy consumption; c) coarse product reject outlet for hard materials; d) operational reliability; and e) industrial scale throughput.

2.6 Other mills

2.6.1 Hicom mill

The Hicom mill has been developed by Hicom International Pty Ltd. which is a subsidiary of C.H. Warman group of Australia since the end of 80's. Recently, this mill has become commercially available and has found its first industrial application in diamond processing plants (Boyes, Hoyer and Young, 1997). It applies the principle of centrifugal milling through a special combination of grinding chamber geometry and motion. The grinding chamber is approximately conical in shape with a hemispherical base and is suspended about a vertical axis. It undergoes a rapid circular oscillation referred to as nutating motion, much in the manner of a conical flask being shaken by the wrist. This causes the contents of the chamber to tumble rapidly in an induced acceleration field, in this case typically 40 to 50 times gravity. Figure 23 shows the current Hicom mill in the first industrial application. The model is a 55 kW unit with a 120 mm diameter feed throat and 30 litre grinding chamber. The nutating geometry allows the mill to accept feed from a conventional feed belt or hopper in a relatively stationary feed throat. The mill geometry also gives rise to a net acceleration in the direction of flow. In continuous operation material is drawn

through the mill and positively discharged with minimal back mixing. The main advantage of this mill is in an autogenous milling process without any grinding media. The intense grinding action of the mill in combination with its low residence time and near plug-flow transport characteristics makes it suitable for a diverse range of some industrial applications. Hicom mills can operate with a charge of steel ball or other media, or, alternatively, with an autogenous charge of ore. Thus the mills are extremely versatile, and specific models are available to suit a very large number of mineral and industrial processes. In particular, the Hicom mills are well suited to energy efficient ultra-fine grinding.

The specific characteristics and operating capacity of this mill suggests that it could be well matched to the needs of the diamond mining industry. Applications have been identified both in the recovery process for marine diamond and in the liberation of diamonds in South Africa and Australia. In the autogenous operation the mill can selectively break shell contaminants from marine diamond concentrates and fully liberate diamonds from ores without damage to the diamonds. Figure 24 shows the simplified process flow-sheet including the Hicom mill at Alexkor Ltd, South Africa. The proposed solution was to place a Hicom mill in the flow sheet after the DMS plant, to preferentially grind the seashell to particle sizes below around 1 mm. In addition to diamond liberation, other commercial applications are: a) conventional milling of hard ores to less than 20 μm ; b) autogenous reduction of critical size pebbles in SAG mill circuits; c) fine milling of industrial minerals to the 2 μm range; d) potential application for the milling of ores underground; e) mine back-fill preparation; and f) mechanical alloying of high temperature materials.

Braun, et al., (2002) compared the specific energies required for milling of a limestone material below about 100 μm to the fine products with a dry Hicom mill pilot plant and a typical ball milling circuit. Figure 25 gives the results. It is seen that the reduction in energy required to mill this limestone to fine sizes in the Hicom mill system over what would be expected for the ball milling system. For the material sizes produced during the experiments, the milling energy requirements were between 31 % and 70 % lower than would be expected for a conventional ball milling circuit.

2.7 Product size-energy input relations from various mills

Wang and Forssberg (2001) summarised the product size-specific energy input relations obtained by various recently developed mills such as MaxxMill[®], Drais mill, ESM, SAM and HPRM as well in the comminution of limestone, as shown in Figure 26. Clearly, these new or developed mills have shown a superior performance for size reduction and energy saving compared to the conventional ball mill.

3. Improved and new classifiers

Classification of the ground products from the mills can save energy and avoid over-grinding and increase the unit capacity. An improvement of the slope of the particle size distribution is another objective. Recent work has focused on development and application of new and improved air classifiers and centrifuges, especially for classification of ultra-fine particles (Braun, *et al.*, 2002; Adam, *et al.*, 2001; Wang, *et al.*, 1997; Timmermann and Schönert, 1997).

3.1 Air classifiers

3.1.1 Turboplex with new wheel design

Hosokawa AlpineAG & Co., Germany has designed a new wheel for Turboplex classifier (Adam, *et al.*, 2001). This new classifying wheel 500 ATP-NG of a production-scale classifier is shown in Figure 27. In this new wheel, the rigid-body flow begins at the elbow of the blade. In the out area, a vortex forms, which replaces external pre-acceleration of the classifying air and ensures that the air flows uniformly through the interior of the rigid body. To obtain a uniform distribution of the airflow over the wheel length, the blades are drawn in at different widths towards the centre of the wheel- less towards the fines discharge and more to the hub side. The classifying wheels with the new blade geometry with diameter of 200 and 315 mm underwent extensive testing in the Alpine test facility. The purpose of reducing the pressure loss was achieved to a complete satisfaction (Figure 28). In the fines range $d_{97} < 5 \mu\text{m}$, the pressure loss of a Turboplex with the new wheels at the same fineness is only about a half that of a normal classifier. As a result, blowers with low pressure can be used, leading to an around 40 % energy saving.

3.1.2 V- and VSK-separators

In order to efficiently classify finer particles from the pressed agglomerates from the HPRM, KHD Humboldt Wedag, AG, Germany has developed a new dry classifier so called V-separator (Farahmand, *et al.*, 1997), which owns its name to the particular shape. The V-separator is a purely static separator without moveable components. It measures about 6 meters high. The feed material is classified by a counter current airflow while it cascades down a series of steps in the form of louvers. During this operation the fine particles are extracted from the cascades and transported upward. The coarser particles drop downward due to gravity. The cut is exclusively made by regulating the airflow. Intense material movement through the cascade is of vital importance. The particles, especially the coarser ones, are accelerated during this operation and deagglomerating by impinging on the cascades. This separator type was first applied at the Hyundai cement plant in South Korea. With the successful industrial application of V-separator, the KHD also developed a combined VSK classification system with V- and SK- separators for a purpose of fine classification (Farahmand, *et al.*, 1997). As seen in Figure 29, a dynamic SK-separator with a cage wheel has been mounted downstream of the static separator (V-separator). The dynamic section had to be arranged horizontally. This VSK separator allows deagglomeration, primary classification of the broken up material, and secondary classification in a single machine. The speed of the rotating cage wheel is again determining with regard to the fineness required for the finished product.

3.1.3 Inprosys air classifier

The inprosys air classifier was developed by the SINTEF, Norway (Braun, *et al.*, 2002). Figure 30 shows the schematic drawing of this classifier. As seen, the feed material enters the classifier suspended in air through a vertical pipe positioned at the bottom of the classifier. The classification takes place in the classifying chamber. After passing the feed dispersion cone, the coarse material is discharged from the classifier by gravity through the coarse fraction outlet. Remaining material rises with the air stream to the top of the classifier. A rotor accelerates the materials to its peripheral speed thus creating a centrifugal force in the particle to act against the air

drag forces. As the particles move towards the inside of the rotor and are accelerated to its peripheral velocity, a Coriolis effect is generated. As particle velocity increases, the centrifugal force increases and coarser particles can be rejected outside the rotor, while finer particles pass through the rotor and are discharged from the classifier fines outlet. A secondary air inlet, supplying the classifier with an additional air stream, is used to clean the coarse fraction from the very fine particles agglomerated on the surface of the coarser grains. This results in an improvement of the classification efficiency.

3.2 Centrifuges

Without a suitable classifier for classifying ultra-fine particles when the required cut size is in the range of 0.2-1.0 μm , it is difficult to reach a high efficiency in the production of ultra-fine particles. Recent development on this aspect is to utilise the existing centrifuges and to develop new equipment based on centrifugation principle.

3.2.1 Disc-stack nozzle centrifuge

One development is the use of disc-stack nozzle centrifuges in chemical industry. Its advantage over hydrocyclones and other centrifuges is the capability of treating a dense feed slurry up to ~ 20 vol. % solids. Figure 31 shows a schematic of a large-scale disc-stack nozzle Model QX210-30B centrifuge (Wang, Forssberg and Axelsson, 1997). This type of centrifuge is designed for re-circulation of a part of the nozzle discharge to the bowl. The re-circulated stream of the underflow product is not mixed with the feed but is taken down to the bottom of the bowl, where it enters a special distributor. The distributor sends out the re-circulated material through re-circulation tubes to the vicinity of the nozzles. Thus the re-circulated material is sent back to the nozzles without interfering with the separation of the feed. The nozzle discharge is collected in a de-foaming pump and then split into two parts, one being re-circulated and the other being drawn off. By varying the relative amount of re-circulated material it is possible to influence the classification. If more under-flow material that is drawn off the finer will the particle size distribution of the overflow be. The more one re-circulates and the less is drawn off, the higher is the concentration of solids in the material drawn off. The nozzles in the machine are situated in the perimeter of the slurry space and the coarse particles of the under-flow are continuously discharged through these nozzles. The QX machine as a classifier is used mainly to classify the materials into coarse and fine products. The rate of nozzle discharge depends upon the number and size of the nozzles, i.e., their inner diameter. In the machine, there are 12 openings for the installation of nozzles. This QX centrifuge consists of 65 discs and the thickness of the spacer between the discs is 1 mm. The feed rate or the split (a volumetric ratio of overflow rate to feed rate) should be limited below the flooding level of the QX centrifuge. Its capacity is $20 \text{ m}^3 \text{ h}^{-1}$.

Studies (Wang, Forssberg and Axelsson, 1997) on wet classification of a calcite (size: $100\% < 8 \mu\text{m}$) and a kaolin clay (size: $100\% < 20 \mu\text{m}$) in the centrifuge have been carried out to obtain filler and coating grade pigments with a fineness of $90\% < 2 \mu\text{m}$. Figure 32 shows the classification performance plots of the centrifuge for both calcite and kaolin clay under various operating parameters. The percentage of $< 2 \mu\text{m}$ or $< 1 \mu\text{m}$ particles recovered to the overflow is plotted against the solids concentration of the overflow. When the solids concentration of the feed was held constant, i.e., 20 vol. % solids, overflow concentration was varied by changing the rate of the overflow. The

relationship of the recovery of the ultra-fines vs. the solids concentration of the overflow appears to be almost linear. The fineness of 90 % < 2 μm in the overflow product can be achieved with a recovery of up to 50 % under optimum conditions. If a centrifuge is used in a closed loop grinding circuit, an improved recovery of fines in the overflow means a small fraction of the coarser particles rejected from the centrifuge which need to be ground. Another index in the optimisation is the content of ultra-fine particles < 2 μm in the overflow. It is evident that if a high content of particles < 2 μm is required, the recovery of the fines drops very rapidly. This leads to only small savings in the grinding power since the under-flow rate will be high. Moreover, a total process optimisation is needed to give answers to which are the best values for the contents of particles < 2 μm in the overflow and in the feed. In some cases multi-stage classification may be an advantage. Furthermore, a benefit obtained by this centrifuge is to improve the slope of the particle size distribution of the final product. Figure 33 shows the results from one stage classification. For both calcite and kaolin clay, centrifugal classification shows a significant effect in improving the slope of the size distribution curves at ~ 20 % by volume solids concentration of the feed. The particle size distribution of the overflow product becomes narrower and finer after removal of the larger particles from the feed.

The classification of various calcite materials (< 8 μm , <12 μm and < 45 μm) has also been studied with respect to feed size (Wang and Forssberg, 2001). The selection of a split appropriate for an efficient separation depends on the particle size distribution of the feed. The highest recovery of the desired particles (< 2 μm) can be obtained with a satisfactory fineness of the overflow product (90% < 2 μm) for the treatment of a feed material <12 μm . An excessive amount of fine or coarse calcite particles in the feed affects the efficiency of the classification using the QX centrifuge.

Numerous large-scale disc centrifuges have been successfully applied to industrial classification/degritting of clays in New Zealand and Brazil. The main operating conditions for industrial application in a Kaolin processing plant, New Zealand are (Klein, Personal Commu., 1997):

- G-force: 4000 Gs;
- Size of nozzle: 1.6 mm;
- feed rate: $\sim 90 \text{ m}^3/\text{h}$.

3.2.2 Centrisizer

According to the growing requirements for the production of ultra-fine powders, KHD Humboldt Wedag, Germany has developed an improved version of the decanter centrifuge named Centrisizer (Figure 34). Unlike the counter-current flow version of conventional decanter centrifuges, this machine has been improved based on the theory of direct current separation. The essential difference to conventional decanter centrifuges is that the suspension is fed to cylindrical drums and both separated products as well as fine and coarse materials are discharged from the opposite side of the drum. The complete length of the drum is available for classification. Because of the constant flow direction, a crosscurrent sedimentation is achieved. Problems with the transportation of solid particles in the conical section of the drum as are well known with conventional centrifuges used for classification, especially for very fine materials, are eliminated. The long cylindrical rotor provides a large settling area. The machine was used for the production of fine materials in the range of <1 μm (anatase) to < 20 μm (limestone), operating as a cross current classifier at centrifugal

acceleration between 100 and 2000 G (Muller, Kompe and Kluge, 1993). For the classification of an anatase < 1.5 μm and a limestone < 20 μm , the product fineness of d_{99} between 0.7 μm to 15 μm could be attained at approximately 30 wt. %. The results showed that the decanter centrifuge could be used for both classification and de-gritting.

3.2.3 TU Clausthal centrifuge

Technische Universität Clausthal in Germany has developed a new counter-flow centrifuge (Timmermann and Schönert, 1997). Figure 35 shows the sketch of this centrifuge. It consists of a bowl centrifuge into which clean fluid is introduced through a porous media. The process chamber has three sections: fluidised bed zone, classification zone and overflow zone. The fine product is directly discharged with the overflow water. The coarse products settle outwardly, builds up a fluidised bed and is aspirated. All process streams enter or leave the centrifuge by rotating joints. This centrifuge was first utilised to classify fine quartz and calcite. The fine material recovery is between 88 % at a size cut of 2 μm and 65 % at a size cut of 1 μm . The coarse product load can be increased up to 30 vol. % which corresponds to 50 wt. % for quartz and calcite. Figure 36 also shows a comparison with other different classifiers like Centrisizer, Alpine-Hydroplex and Fryma classifier in the classification of a calcite fine below 20-30 μm (Timmermann and Schönert, 1995). The results indicated that the grade efficiency curves obtained by the TU Clausthal centrifuge show a lower bypass and a better imperfection compared to the others.

3.2.4 Counter-flow Rotating Hydro-classifier

A counter-flow rotating hydro-classifier was developed in TU Karlsruhe in Germany (Bickert, *et al.*, 1996), as shown in Figure 37. Particle classification in the classifier is based on centrifugal force fields. This classifier can be used in dry or wet treatment. The feed enters the classifier into the classifying space. If the pressure loss in the coarse stream is increased some of the fluid will pass through gaps to the inside of the rotor and further through the hollow shaft into product collecting. The vanes form a zone of forced vortex where the finest particles must pass through. The centrifugal force obtainable ranges from 200 to 1800 Gs. It was reported (Bickert, *et al.*, 1996) that the classifier can obtain fine products down to 90 % < 3 μm . An advantage is the versatility of the classifier and its capability to classify also a dense slurry with high solids contents. No information is yet available of the classifier capacity. The results showed that the classifier has a poor separation efficiency as it classifies only a partial flow. The result is that the coarse product is rather similar to the feed of the classifier.

4 Other assisted methods

4.1 Grinding aids

One approach for effective size reduction and energy saving is to use a grinding aid or chemical additive in fine comminution. Most of previous results in this aspect have been obtained in the case of tumbling mills (Klimpel, 1982; EL-Shall, *et al.*, 1984; Somasundaran, *et al.*, 1995). Since stirred bead mills have recently attracted attention because of their reported high energy efficiency, ability for grinding into the micrometer and submicrometer range and lower product contamination, some works

(Forssberg and Wang, 1995; Wang and Forssberg, 1995; Zheng, *et al.*, 1997, Tuunila, 1997) have been carried out for this effect. This is because the findings from tumbling mill grinding involving use of a chemical additive will not be wholly applicable to the stirred media milling case, in which smaller grinding media are used, and the pattern and velocity of rotation are rather different. It has been indicated that addition of a favourable chemical additive into the ground particulate material in fine grinding in stirred bead mills to improve the grinding efficiency with less power use. Table 3 lists the chemicals used in stirred media mills: In a study (Wang and Forssberg, 1995), three organic polymers (sodium salt of an acrylic copolymer, sodium salt of a polycarboxylic acid and sodium salt of polymer) and two inorganic chemicals (sodium hexametaphosphate and tetrasodiumpyrophosphate) were used as grinding aids for wet ultra-fine grinding in a dolomite material ($< 70 \mu\text{m}$) in a stirred bead mill. The fineness for the filler product was required to be 90 % less than $2 \mu\text{m}$. The results indicated that the polymeric chemicals have a superior effect on the grinding action, as compared with the inorganic chemicals. The more effective size reduction and energy saving requires properly viscous slurry conditions, which can be controlled by a smaller amount of the polymeric chemical like polycarboxylic acid (Figure 38). They also found that the periodic addition of the polymeric chemical into the ground slurry during the process could enhance the grinding rate and the specific energy efficiency. A steeper size distribution of the product can be obtained by adding the polymeric chemical periodically. Zheng, *et al.* (1997) studied the effect of additives on the wet grinding of limestone in a stirred bead mill. The chemical additives chosen were representative inorganic electrolytes (sodium hydroxide and sodium carbonate), a surfactant (sodium oleate/oleic acid) and a polymer (polyacrylic acid or PAA). Figure 39 shows the results of average energy efficiency over the additive concentration at various chemicals. Compared with grinding without additives, use of sodium carbonate and sodium oleate results in a decreased energy efficiency at high concentrations over the additive concentration range studied while use of sodium hydroxide results in an increased efficiency only at the lower concentration of 0.008 %, but decreased efficiency at higher concentrations. However, use of oleic acid and the PAA produced a beneficial effect at the higher concentration of 0.1 % but either no effects or detrimental effects depending on the additives type and the concentration. The PAA was found to be among the best additives for improving the grinding energy efficiency. Furthermore, a work (Tuunila, 1997) indicated that sodium carboxymethyl cellulose is recommended as a more effective grinding aid among others (such as polycarboxylic acid, etc.) when a gypsum was wet ground in the stirred bead mill.

Besides chemical additives used in wet milling, effective role of chemical additives for dry grinding of carbonate minerals in stirred media mills has been examined (Forssberg, *et al.*, 1995; Wang, *et al.*, 2002). It is known that particle aggregation/agglomeration causes poor flowability of dry material to be ground in a mill. Also, grinding media and liner coating results in a poor dry grinding efficiency due to the cushioning effect. Forssberg, *et al.* (1995) studied that an addition of 0.1 wt % of Berolamine (a mixture of trietanolamine, dietanolamine and etanolamine) into a dolomite material being ground with an agitated media mill SAM resulted in an increased of the product fineness with less energy consumption. Figure 40 shows the particles below $10 \mu\text{m}$ increases by 20 % in the presence of the grinding additive at the similar energy input. However, it is interesting to see that the use of amine for dry milling of dolomite did not affect the breakage of the coarser fractions, but only had a

significant effect when the finer fraction built up in the SAM. This is due to the finer particles being more susceptible to agglomeration. As a surface active grinding additive, amine is a hetero-polar organic compound. Molecules of the compound adsorb on the solid surface by their polar functional group, thus decreasing the surface energy or coat the external surfaces of fine dispersed particles, thereby preventing their agglomeration or act as lubricant on shell and media to prevent powder coating and influence their flowability. Due to the physical absorption, the surfactant-coated particles alter the grinding actions of particle-particle as well as particle-media. The forces involved in the physical absorption may be London-van der Waal forces. The molecules are physically adsorbed on the particles. This involved approaching the solid surface along a low-energy path. This consequence of the decrease in the frictional forces is favourable to increase the flowability of dry material. On the other hand, the use of amine, particularly triethanolamine, was found to be only effective in the cases of some softer minerals such as calcite (Sohoni, *et al.*, 1991).

Table 3 Chemicals used as grinding aids for fine grinding in stirred media mills

Chemical	Type	Ground material	Milling mode	Reference:
Tetrasodium pyrophosphate	liquid	dolomite	wet	(Wang, <i>et al.</i> , 1995)
Sodium hexametaphosphate	liquid	dolomite	wet	(Wang, <i>et al.</i> , 1995)
Sodium salt of an acrylic copolymer	liquid	dolomite	wet	(Wang, <i>et al.</i> , 1995)
Polycarboxylic acid	liquid	dolomite, limestone,	wet	(Wang, <i>et al.</i> , 1995, 2002; Zheng, <i>et al.</i> , 1997; Laapas, <i>et al.</i> , 1984)
Sodium hydroxide	liquid	limestone	wet	(Zheng, <i>et al.</i> , 1997)
Sodium oleate	liquid	limestone	wet	(Zheng, <i>et al.</i> , 1997)
Oleic acid	liquid	limestone	wet	(Zheng, <i>et al.</i> , 1997)
Sodium carboxymethyl cellulose	liquid	Limestone, gypsum	wet	(Wang, <i>et al.</i> , 1995; Tuunila, 1997)
Triethanolamine	liquid	dolomite	dry/wet	(Wang, <i>et al.</i> , 1995; Laapas, <i>et al.</i> , 1984)
Mixed triethanolamine/diethanolamine	liquid	dolomite, limestone	dry	(Wang, <i>et al.</i> , 1995 and 2002)

4.2 Microwave-assisted

Microwave is a form of electromagnetic energy with associated electric and magnetic fields. The materials that absorb the microwave radiation are termed dielectric and contain dipoles. When the microwaves are applied to dielectric materials the dipoles align and flip around since the applied field is alternating. Subsequently, the material heats when stored internal energy is lost to friction. Typically natural materials, like ores contain various minerals, which have very different mechanical and thermal properties. When the energy is applied, stresses of different magnitudes can be created within the lattice, both by the heating and cooling processes. This is due to significantly different thermal expansion coefficients existing between different mineralogical species. The stresses lead to localised fractures of an intergranular and transgranular nature but not necessarily to catastrophic failure. These fractures may lead to a significant reduction in comminution resistance. Thermal stress fracture is generated in the microwave-assisted comminution of minerals. The fractures are induced along the grain boundaries between the different minerals as a result of the difference in the absorption behaviours and the thermal expansion coefficients of the materials. Microwave energy treatment can reduce the work index of certain materials, which favours the subsequent processes for efficient size reduction, separation with less energy.

The application of thermal energy to assist with mineral or material fracture and liberation by microwave heating has been an interesting subject (Wang, *et al.*, 2000; Kingman, *et al.*, 1999 and 1998; Gungör, *et al.*, 1998; Haque, 1998; Xia, *et al.*, 1997; Salsman, *et al.*, 1997; Florek, *et al.*, 1995; Walkiewicz, *et al.*, 1991 and 1988; Chen, *et al.*, 1984). The present microwave technology is bringing into commercial use for a revolutionary new process to recover gold, copper and other metals from refractory ores. It was reported that the microwave has a significant impact in the processing of platinum group and base metal ores, and heavy mineral sands (Bateman Project Holdings, 2000). A study performed by Wang and Forssberg (2000) indicated that the particle size has a significant effect on the microwave heating behaviour and the grind-ability of the pre-heated material. Thermal stress fractures in a coarse fraction (-9.50+4.75 mm) of limestone and quartz could be affected by microwave heating to varying degrees, resulting in an increased fineness of the ground powder product in a subsequent dry ball milling. The industrial minerals (dolomite, limestone and quartz) were difficult to heat in lower microwave energies (< 7 kW) during an exposure (< 30 min), particularly to the finer material below 4.75 mm. The use of microwave energy to assist milling of the silicate and carbonate minerals is inappropriate due to their thermal insensitivity in microwave exposure. However, they tested a copper ore associated with sulphide, showing microwave sensitive. The thermal stress cracks in the copper ore occurred readily. A better liberation of sulphide minerals in the ore matrix was obtained when the ore pre-heated by microwave was crushed. The selective fractures along the sulphide-gangue mineral grain boundaries cause a better and cleaner liberation of sulphide mineral particles from the ore matrix. Also, this can reduce the energy input in a subsequent grinding for the mineral liberation. The cleaner liberation may favour the subsequent extractive processing like flotation. This aspect needs to be further investigated.

4.3 Ultrasound-assisted

The fragmentation effect of ultrasonic fields in suspensions and solids has been studied since 1950s. Gärtner (1953) attempted firstly to utilise ultrasonic waves in the fragmentation of particles. His results were poor. Another study (Graff, 1979) concerned the arrangement of transducers in a multi-stage mill. Quantitative information on the success of these work is scarce. Leach (1988) investigated the fragmentation of resonant rocks samples fixed to the tip of an ultrasonic transducer to observe a preferred fracture at the node. Lo and Kientzler (1992) evaluated the Tarpley nip roller machine, using the device to grind mineral specimens. Their results showed energy consumption similar to that of a ball mill. Menacho, *et al.* (1993) performed a comminution test with and without ultrasonic pre-treated samples in a ball mill. The pre-treated mineral exhibited a higher grinding rate of 32 %. The majority of the devices mentioned above were composed of a stationary vibrating surface opposing a passive rotating device that nips the particles in a gap that is smaller than the feed particle size. The ultrasonic vibration amplitude is about an order of magnitude smaller than the gap. The low processing capability attained with this design limits the method application, in spite of the very low energy consumption claimed. A recent work (Gaete-Garretton, *et al.*, 2000) presented to apply ultrasound energy to grinding in a high pressure roller mill (HPRM). As shown in Figure 41, the design is based on a HPRM in which one of the rollers can be ultrasonically activated. In the approach, the device retains its higher performance, extending its ability to the efficient treatment of hard materials like granite and quartz. The rollers apply mechanical stress to the material, facilitating the breakage process and coupling the active roller to the particles being ground. To achieve a lower specific energy consumption, the active roller was designed as an ultrasonic vibrator piezo-electrically driven at its third longitudinal resonant mode. Figure 42 shows that the particle size distributions in the ultrasonic roller press machine and in the ball mill are approximately the similar. However, the processing time was 40 min for the ball mill and only 1.85 min for the ultrasonic machine. In addition, the rate of energy consumption in the ultrasonic machine was 6.8 kWh/t and for the ball mill, the value increased to 20 kWh/t. The results in Figure 43 show that when ultrasonic energy is applied, the total consumed power diminishes inversely to the ultrasonic power applied. The total power needed by the process drops by approximately 15 % for an applied ultrasonic power of approximately 100 W. these results suggest that it would be interesting to explore the application of even higher ultrasonic power than that tested in their study.

5. Control, modelling and simulation

5.1 On/In-line control and analysis for ground product

In-process measurement of particle size distribution provides continuous analysis, quality control and optimisation of product yield for various industries like mineral, cement, pharmaceutical, chemical, food, pigment, fillers/coating and powder metallurgy. As process production rates continue to improve, the delay between laboratory analysis and process correction of the product stream become more significant costly in many commercial applications. Elimination of sample handling and operator manipulation is now possible for most pneumatic flows using optical methods (normally laser beam or image analysis) or for slurry flow using an

ultrasonic extinction technique, which are properly interfaced with the process stream. The demand for continuous control of fine grinding circuit has led to recent developments on on-line/in-line particle sizing devices (Greer, *et al.*, 1998; Puckhaber, *et al.*, 1998; Kalkert, 1999 and Schwechten, *et al.*, 2000). As known, grinding circuits are notoriously unstable and unwanted fluctuations in particle size, pulp density and volume flow rates can result in the inefficient use of grinding capacity and energy efficiency and to poor extraction of valuable minerals.

Normally, the on-line/in-line instruments are divided into two categories, namely stream scanning and field scanning (Allen, 1990). In the former, individual particles are observed, counted and sized, whereas in the later the size distribution is deduced from the interaction between an assembly of particles and a measuring device. In stream scanning, particle size may be determined by the amount of light cut off by a particle as it passes through a light beam or by collecting and measuring the scattered light. Basic counters pick up the light scattered in the forward direction but a greater sensitivity is obtained by incorporating a light-collecting device such as an elliptical mirror. These instruments are usually applied to dilute systems. Field scanning techniques are dominated by the low-angle laser light systems, of which several versions exist for the measurement of dry powders (Witt, *et al.*, 1996 and Malcolmson, *et al.*, 1998). These instruments yield reproducible particle size distributions. The other field-scanning instruments employ ultrasonic extinction (or attenuation) to generate a particle size distribution from the production line of a concentrated suspension (Greer, *et al.*, 1998). In addition, image analysis technique is also one option for on-line/in-line measurement of relatively coarse particles.

The demand for continuous control of particle processing circuits has led to the development of some on-line or in-line particle size analysis devices. These devices, which are commercially available, can be classified into two categories according to the measurement of various product streams, dry particles in air and liquid particles in suspension. A survey report (Wang and Forssberg, 2000) has demonstrated that the commercially available instruments for on-line/in-line particle size analysis are suitable for use in obtaining particle size distributions by means of laser diffraction or ultrasonic extinction or image analysis, even with very fine powders. Eight instruments for dry particle analysis and the five instruments for suspension stream analysis have been found. The instruments based on either laser diffraction or ultrasonic extinction can be used for fine particles down to 0.1 or 0.5 μm . The image analysis technique is used for on-line measurement of relatively coarser particles. The instruments such as the Insitac EPCS from UK and the Sympatec MYTOS & TWISTER (Germany) for dry powder, and the Sympatec OPUS for suspensions are user friendly with good software control systems under Window environment. The Sympatec company, Germany has extensive experiences on dry dispersion technology. Sympatec and Malvern/Insitac both have developed their methods for on-line/in-line sample handling before measurement. These instruments have been widely installed in various industrial production lines. For instance, the KiMA Echtzeitsysteme GmbH, Germany has produced an on-line particle size analyser called "Online Particle Sizer". In the instrument, a laser beam is scanned rapidly and focussed down to a micron scale by a lens. This produces a fast moving laser focus, which scans a region in space. The transmitted laser energy is collimated by another lens system and directed onto a fast detector, which only measures intensity. Particles to be measured fall through the focus region and block the beam while it scans over

them. The range of particle sizes is 2-500 μm . This system can continuously deliver information, which can be used immediately by conventional control systems. This particle size analyser can be used in milling processes, milling control and quality control. Figure 44 shows the schematics of a ball mill with the Online Particle Sizer and a Fuzzy Control Engine (FCE). The FCE is connected to the existing PLC and adds its capabilities. Fuzzy control is a way to control the machinery of a grinding plant in a robust and cost effective way. The control strategy is set up in natural language. This means that the experience of plant and automation staff can be effectively implemented. The control system uses a lot of parameters, which are nearly impossible to handle in the conventional way. As a result, there exist lots of sophisticated grinding plant controllers, which are highly stable, even at start up or shut down and which can be well understood and supported. With the Online Particle Sizer, one of the most important parameters of a grinding plant is available and can be inserted into the complex control strategy. This can lead to a higher quality product with lower energy required and reduced cost in producing powder like cement. The first installation of the system took place recently in cement industry (Kalkert, 2000 and KiMA, 2000)

The CSIRO Minerals, Australia has developed an acoustic emission (AE) soft-sensors for the control of the processing systems (see Figure 45). The AE is mechanical waves arising from the rapid release of strain energy within a stressed material. Sources may be defect related deformation processes, impacts, shear, abrasion and particle breakage. Energy radiates from a source as elastic waves, which can be detected at the material surface (typical 10-1000 kHz). The significant areas of work on surface vibration (AE) passive monitoring of process variables/machine condition are: a) grinding mill; b) hydrocyclones/DM cyclones and c) slurry pipeline. The multiple AE transducers are installed on the rotating AG/SAG mill surface or on stationary DM cyclone shell in order to log and analyse the data. This CSIRO technology has been in some field trials in mines around Australia, South Africa and Chile.

5.2 Modelling

Models for each comminution process are useful for some purposes such as process design, performance evaluation and assessment, equipment and process scale-up but most importantly for simulation. Many mathematical models were developed primarily to provide the basic elements for simulation. These models mainly involved empirical, phenomenological and fundamental models as well (Herbst, *et al.*, 2002). The empirical models, which are so called black box models, are a set of algebraic expresses by regression, multivariate statistics or neural networks (*e.g.*, Bond's equation is a semi-empirical model). The phenomenological models are a set of algebraic and differential equations arising out of application of some engineering, physics and chemistry (*e.g.*, population balance model). The fundamental models are a set of algebraic and differential equations based on the basic laws of physics and chemistry (*e.g.*, discrete element method or computational fluid dynamics). Figure 46 shows the model hierarchy. Model development for comminution (particularly for ball mills) can be roughly divided to three periods (Herbst, *et al.*, 2002):

In early the 1960's, some researchers (Bond, 1952; Holmes, 1957; Charles, 1957; Schuhmann, 1960) had proposed laws relating energy for breakage to simple parameters due to the absence of low cost digital computation and the corresponding

programming languages available. Bond (1952) concluded that work input to break a cube of side x_1 is proportional to the volume x_1^3 of the cube, but on formation of the first crack, the energy flows to the resultant new surfaces, such energy being proportional to x_1^2 . When an irregularly shaped particle is broken, the strain energy is irregularly distributed, and hence the energy required for breakage lies between x_1^3 and x_1^2 , the geometric mean being $x_1^{2.5}$. Thus, the number of particles of assumed similar shape per unit volume will be proportional to $1/x_1^3$, so that the work input a unit volume was taken to be $x_1^{2.5}/x_1^3=1/x_1^{0.5}$. In reducing a fixed size x_1 to a product size x_2 , the Bond work index formula is expressed as:

$$\bar{E}_A = W_i \left[\frac{10}{\sqrt{x_2}} - \frac{10}{\sqrt{x_1}} \right] \quad (4)$$

where x_1 and x_2 are expressed in microns as the size associated with 80% passing. Holmes (1957) introduced a variable exponent r in place of the power of 0.5 used by Bond, producing

$$\bar{E}_A = W_i \left[\left(\frac{100}{x_2} \right)^r - \left(\frac{100}{x_1} \right)^r \right] \quad (5)$$

thus allowing lines of any desired slope on the energy utilisation plot. Charles (1957) also incorporated a variable exponent into the energy equation but in the context of the size modulus of the Schuhmann plot. Based on the Charles' concept, Schuhmann (1960) expressed the energy for breakage as:

$$\bar{E}_A = A(x')^{-n} \quad (6)$$

where n is the slope of the straight-line portion of the Schuhmann plot. Among these models, the Bond's formula has been more popular to be used for ball mill circuit design and process analysis for comminution devices/circuits as well.

During a period of the 1960's-1980's, some researchers (Lynch, *et al*, 1967; Mular and Herbst, 1980; Laguitton, 1984; Ford and King, 1984) have used phenomenological models for analysis and optimisation of comminution circuits. The common one is based on the population balance methods (PBMs). The PBM simulation approach was investigated extensively in the 1970's and early 1980's. The population balance equation provides a powerful model for the description of industrial comminution devices. It allows the development of a uniform model that describes the operating behaviour of rod, ball, semi-autogenous and autogenous mills. The fundamental population balance model for any comminution process is:

$$\begin{aligned}
& -\tau \frac{d\kappa(x)p(x)}{dx} + 3\tau\kappa(x) \frac{p(x)}{x} + \tau\mathfrak{R}(p(x), x, F[p(x)]) \\
& - \tau \int_{R(x)} \mathfrak{R}'(p(x'), x' F[p(x')]) b(x; x') dx' - \tau \int_{R(x)} 3\kappa(x') \frac{p(x')}{x'} a(x; x') dx' \quad (7) \\
& = p_{in}(x) - p_{out}(x)
\end{aligned}$$

where p is the mass fraction of particle in a certain size, κ is the specific rate of breakage of material, τ is the average residence time in a comminution device, \mathfrak{R} is the rate at which particles at co-ordinate position are destroyed, b and a are the non-linear functions. It has been indicated that the phenomenological models provide a much superior prediction of circuit performance rather than the empirical model (Herbst, *et al.*, 2002). Figure 47 shows the respective predictions of a modified Bond model, in this case presented as a family of curves labelled with each work index value and of a general simulator JKSimMet (including PBMs), as well as the experimental data points. Clearly, the ore work index was essentially constant over the period of the testing, but the phenomenological models predicted the circuit performance.

In the late 1980's and early 1990's, the application of Discrete Element Methods (DEM) to grinding simulation was investigated by Mishra and Rajamani (1992). The DEM involves tracking the motion of a large number ($< 10^6$) of discrete elements (balls) in response to the applied forces within a mill. Essentially, this involves the solution of a very large set of differential equations describing the translational and rotational motion of each element in 2D or 3D space. Recent activities on this aspect have been focused on the increase of computational speed to reduce simulation time and solve bigger problem (Rajamani, *et al.*, 2001). The shear and impact energy dissipation spectra are particularly useful in the estimation of liner wear (Qiu, *et al.*, 2001). A phenomena that can be incorporated in the DEM computations to study the effects on such factors as power and the energy spectra over time. The DEM in simulations focus on discrete "particles" by solving Newton's second law of motion applied to a particle of mass, m_i , moving with the velocity v_i when it is acted upon by the collection of forces f_{ij} including gravitational forces and particle-particle, particle-fluid, and particle boundary interactive forces:

$$\frac{d(m_i v_i)}{dt} = \sum f_{ij} \quad (8)$$

A recent development is the prediction of comminution results based on the energy spectra. Bwalys, *et al.* (2000) and Buchholtz, *et al.* (2000) have described the methods of incorporating breakage into DEM simulation. It is also reported that ways of using both PEM and DEM modelling for comminution purposes are of particular interest to industry as it builds on the proven strengths of both approaches to extrapolate into new application in simulation technology. In addition, mathematical equations for computational fluid dynamics (CFD) have been recently used for simulation of particle/ball and slurry motion in mill. Models for discrete grain breakage (DGB), combining with the DEM, have been applied in breakage behaviours of particles by a ball (Herbst, *et al.*, 2002).

Recent development and application on mills has been mainly focused on two types of equipment, i.e., the roller press under high compressive loads and agitated or stirred mill with small media. Consequently, modelling of the performance of these machines have been carried out for the optimisation purpose.

Modelling for the performance in high pressure roller mills have largely been restricted to describing product size distribution curves from the lab scale machines using the self-similarity principle (Kapur, 1972; Fuerstenau, 1991). However, recent work have been made on the performance models, which are able to describe the throughput and power draw in addition to the particle size distribution (Lim and Weller, 1997; Morrell, Tondo and Shi, 1997). Lim and Weller (1997) have developed an empirical model for the HPRM throughput. This model takes into account the effects of variation in grinding force (F_{sp}), rolls speed (F_u), maximum feed size (F_T), moisture content (F_w), rolls surface type (F_r) and scale-up factor (F_s):

$$Q = F_r F_s F_w F_T F_u (1 + s \cdot \log F_{sp}) \quad (9)$$

where s is a constant of measuring the sensitivity of the specific throughput to changes in specific grinding force. Also, Morrell, et al (1997) have derived models for the prediction of power draw, product size distribution and throughput as well. A linear model with a correcting factor for the mass throughput, Q , (t/h), is:

$$Q = 3600 \cdot U \cdot L \cdot x_g \cdot \rho_g \cdot c \quad (10)$$

where U is circumferential velocity of the rolls (m/s), L is the length of the rollers (m), x_g is a working gap (m), and ρ_g is the flake density (t/m^3) and c is the correction factor and can be expressed by:

$$c = 1.3365 - 12.759 \cdot U \frac{x_g}{D} \quad (11)$$

where D is the diameter of the roll. In order to verify that these models developed from the lab-scale mills can be used for prediction of the full scale machines, the JKMRRC has recently carried out a work regarding the HPRM model verification and scale up (Shi, 2003). Figure 48 shows the procedure for this work. The four rock materials selected to test were from Rio Tinto, De Beers and BHP Billiton. The surfaces of the roll used were smooth and studded. Figures 49-52 shows the results for the product size distributions and power draw obtained from the experiments in the lab-scale machine and predicted full scale. Also, the prediction of the throughput of full-scale HPRM using the lab-scale data is shown in Figure 53. From this work, it was concluded that the models are able to provide a high degree of accuracy in the prediction of the product size distributions; the throughput predictions are also good for the smoothed rolls in term of tph actually passing between the rolls, but with the studded rolls the throughput prediction appears to be dependent on the relative height of the studs. These models were supposed to put into the simulator JKSimMet for the simulation purpose after this work.

Stirred media mills (including tower mill) for ultra-fine and fine grinding only really differ from one another in terms of the design of the stirrer that they incorporate. Otherwise their operation is identical. They typically comprise a stationary cylindrical vessel, which can be mounted either vertically or horizontally. Figure 54 shows the typical versions of these units. Currently, stirred mills find industrial application in fine (15-40 μm) and very fine (< 15 μm) grinding in Australia (Napier-Munn, *et al.*, 1999; Johnson, *et al.*, 1998). There is good evidence that conventional ball mills are capable of grinding finer than is traditionally accepted, for instance by the application of very fine media, but tumbling mills are ultimately limited in terms of the energy that they can transmit to the media. In order to increase the energy efficiency and optimise the performance of stirred mills, some recent work on the corresponding modelling has been undertaken.

The JKMRC has put efforts to model the size reduction and power draw of tower mills (Morrell, 1993 and Duffy, 1994) and to scale up tower mill using modelling and simulation (Jankovic, 1999). Morrell, *et al* (1993) used the population balance model to predict the size reduction in tower mills. The model used is stated as

$$P_i = f_i - \left(\frac{r_i}{d_i}\right)p_i + \sum_{j=1}^i a_{ij} \left(\frac{r_j}{d_j}\right)p_j \quad (12)$$

where f_i is mass flow of size i in the feed, p_i is mass flow of size i in the product, d_i is discharge rate of size i , r_i is breakage rate of size i and a_{ij} is appearance function (the fraction of size j material broken into size i). To allow for residence time changes brought about by changing the volumetric flowrate of material to the mill, or changes in hold-up of solids caused by changes in mill volume, ball charge or slurry density, the following relation is applied:

$$\left(\frac{r_i}{d_i}\right) = \frac{u}{v} \left(\frac{r_i}{d_i^*}\right) \quad (13)$$

where u is volume of the mill occupied by slurry and v is volumetric feedrate. The volume of the mill filled by slurry can be estimated from the volume of the cylindrical section of the mill between the inlet and outlet, less the stirrer and ball volume. The value of the factor (r/d^*) varies with particle size and typically will be distributed as shown in Figure 55. The particle size at which the maximum rate occurs (x_m) is a function of the ball size and will increase as the ball size increases.

It was assumed that charge density and stirrer speed should be linearly related to the net power in tower mill (Duffy, 1994). The net power (W_{net}) equation can be expressed by

$$W_{net} = kH_b N_s \rho_c D_b^{0.111} D_s^a T^b \text{ (kW)} \quad (14)$$

where k is calibration constant, H_b is height of ball charge (m), N_s is helical screw stirrer speed (rpm), ρ_c is charge density (tonnes/m³), D_s is helical screw diameter (m), T is number of turns of the helical screw per start, D_b is mean ball size and a and b are constants to be fitted to data. The fitted no load and net powers were combined and

plotted against observed gross power (Figure 56). Clearly, the fit is good, which suggests that the proposed stirrer diameter relation is valid.

Jankovic (1999) continued to investigate the scale up of tower mill using modelling and simulation. The purpose was to study the validation of model from a lab scale mill (0.1 kW) to the full-scale mills (150-920 kW). The designed procedure for the scale up was 1) lab tower mill test, 2) grinding table test, 3) breakage rate fitting, 4) collision frequency, 5) breakage rate scale-up and 6) pilot and full scale mill simulation. The power scale-up and the breakage rate scale-up were found to follow the relations:

$$\frac{P_{industrial}}{P_{lab}} \left(\frac{B_{lab}}{B_{industrial}} \right)^{1.64} = K \quad (15)$$

$$\left(\frac{r_i}{d_i} \right)_{industrial} = \left(\frac{r_i}{d_i} \right)_{lab} K \quad (16)$$

Figure 57 shows the results of the breakage rate scale-up obtained from the predication by modelling and experiments. The simulated and experimental results for the tower mills at various locations in Australia are given in Table 4. It is seen that the simulated data match the experimental results properly except for the grinding a nickel concentrate at Mt Keith. Therefore, it can be concluded from this work that the models for tower mills or vertimill developed based on the lab- and pilot scale units need to be improved using industrial data. The scale-up methods can predict the performance of the full-scale units accurately, providing that the work at lab is carried out according to the strictly defined procedures. The developed models and methodologies can be used for the scale-up and optimisation of industrial size vertical stirred media mills. However, the samples used for the scale-up procedure in the lab and pilot test work must be similar size distribution to the industrial mill feed. The another limitation is to require the relatively fine materials for the lab- and pilot mills for the scale-up work.

Table 4 Results obtained from simulation and experiments

Location	Circuit P ₈₀ , mm			Circulating load, %	
	tph	exp	Scale-up	exp	Scale-up
MIM tower mill	36	9	11	95	123
Cannington Pb	32	20	20.3	120	177
Cannington Zn	12	10.9	12	230	176
Cannington Ag	1.6	18	21.2	90	92
Granny Smith	14.8	32	38	120	118
Mt Keith	65	68	82	220	310

Tracer studies on a vertical Sala Agitated Mill (SAM) and a horizontal Netzsch Stirred Mill (LME4) was undertaken, and the size distribution results from solid tracer tests on quartz and calcite were used to determine the breakage characteristics of the pilot-scale mills by the CSIRO Minerals and MIM Process Technologies in Australia (Weller, *et al.*, 2000). In their work, modelling of residence time distributions of the

SAM and the LME4 with respects to various parameters such as mill rotation speed and flow rate was performed based on the population balance model. In addition, the breakage behaviours with the brittle industrial minerals (quartz and calcite) in the vertical SAM were predicted by means of the batch population balance model.

The results show that breakage in a grinding environment in the pilot scale stirred mill closely matched industrial scale mills, which was studied by impulse addition of tracer to the pilot scale mills operated at steady-state hold up conditions. It was indicated that the liquid tracer and fine solids transport through the Sala vertical mill, as determined by the corresponding residence time distributions, are the same provided that the hold-up is maintained constant. The residence time distribution of the mill is independent of whether the feed is introduced at the top or the bottom of the mill. Modelling of the residence time distribution of the Sala machine is not as strongly compartmentalised as in the case of the Netzsch mill. Also, the breakage results show that the batch population balance model can reasonably be used to determine the cumulative breakage function and breakage rate for material in the SAM operating at steady state hold-up (see Figures 58 and 59). However, the accuracy of the fitting procedure is dependent on the selection of size fraction data and whether the mode of breakage is regarded to be independent of time. There is a reasonable match of the best data fitting model results to experiments. On the basis of the results, the cumulative breakage functions and breakage rates of quartz and calcite tracer in the SAM are roughly power law functions of particle size above a lower size limit. There is an evidence of what may be a strong change in the grinding characteristics of quartz and calcite near the finest grinding sizes for the SAM. However, this may be a function of particle sizing experimental technique.

It was found that the population balance model used in the study is only strictly appropriate for a single mixer model of breakage of impulse injected tracer in a steady-state hold-up stirred mill. They suggested that a possible significant improvement in the model accuracy could be gained by formulating and solving an appropriate population balance equation that directly incorporates flow effects modelled by multiple mixers in series. This approach would directly utilise the optimal number of mixers and associated mean residence times gained from the analysis of residence time distribution. An even more sophisticated approach would be a coupled convection-diffusion and population balance model for charge transport along the axis of the stirred mill during the comminution process.

The group of Computational Fluid Dynamics, CSIRO Minerals has developed the model for a 4-litre Netzsch horizontal bead mill based on the computational fluid dynamics (CFD) (Lane, 1999). A number of CFD simulations have been carried out adopting several alternative approaches to simulating the flow in the horizontal mill. These methods involved: a) A model was set up to represent the entire mill interior as close as possible to the manufacturer's specifications, including the rotor shaft with nine discs each with five holes. b) To study the flow in some detail, a small section of the mill was modelled, which neglecting end effects may be regarded as the basic repeating unit in the mill. c) The modelling of the entire length of the mill. A steady-state approach to the solution was attempted. The flow field prediction was obtained using explicit time stepping, stopping the calculation after 400 time steps of 0.04 seconds with 20 iteration per time step. d) The residence time distribution of ore particles in the mill will be calculated from the CFD modelling.

Figure 60 shows the velocity vectors in a radial-axial plane when modelling the full length of the mill. It was found that the material in the mill has a complex spiralling pattern, where as well as moving in an azimuthal motion in the direction of agitator rotation, there is a series of circulatory mixing cells in the radial-axial plane, where the shearing action of each disc causes the mixture to be centrifuged radially outwards towards the outer wall. The fluid then impinges on the outer wall and is drawn radially inwards again. The distribution of shear rates in a radial-axial plane is shown in Figure 61. Higher shear rates are generated due to the relative movement between discs and the outer wall. The highest shear rates corresponds to the highest local rates of energy dissipation, and it is found that most of the energy dissipation occurs in a small volume surrounding the outer part of the discs and at the outer wall. This means that most of the grinding would be expected to take place in these zones. Thus, it is predicted that grinding of all particles may depend on the circulation of particles in and out of these zones of high-energy dissipation. The results of CFD simulation of the residence time distribution are shown in Figure 62 along with the experimental tracer results. Qualitatively, these results give a similar curve with a very broad residence time distribution, which indicates axial dispersion of slurry particles. Both curves indicates early exiting, with the peak in the distribution occurring considerably earlier than the nominal mean residence time of 80 seconds, and the curves also show long tail. However, the peak in the CFD result occurs at a time only about half of that in the experimental result.

In their summary with the CFD modelling, the present study has shown that a range of information may be obtained by modelling horizontal stirred mills including flow pattern, velocities and shear rate with the mill. This model can also be used to compare power draw, mixing (residence time distributions) and disc wear rates, and hence is expected to be a valuable tool for improving grinding performance while minimising power consumption and wear.

The discrete element method are being applied to model the 2-D performance of the stirred mills in Xstrata Technology (Clark, 2003). The simulation of the wear and grinding behaviours of grinding media with various geometry. From the results, the balls or beads give a higher energy efficiency, compared to the irregular shape media.

The CSIRO Minerals has used a discrete element method to simulate the charge motion in a centrifugal mill with various loadings. The charge in a 30-cm centrifugal mill, used for high intensity and ultra-fine grinding, has been investigated. The cylinder executes a centrifugal motion with diameter 12-cm. The supporting arm rotates at 1000 rpm while the mill cylinder counter-rotates at the same rate. It is filled with uniform 6-mm particles and there are four flat lifters. These parameters were chosen to match the experimental configuration used by Hoyer (1984). The particle distributions, both measured experimentally and predicted by the DEM simulations, are shown below for three different particle loadings. It can be observed that the numerically predicted charge profiles show very close agreement with the high-speed photographs of Hoyer. The 75% and 50% loaded cases exhibit a steady stable charge profile that simply rotates with the mill whilst the granular material deformed smoothly. This is in accordance with the behavior observed experimentally. Furthermore, the charge profiles matched the experiments very closely, with the 75% case being indistinguishable even to the point of predicting the same amount between

the lifter and the charge as the charge separate the lifter at the top. Theoretically there is a complete change in the flow behavior for loads less than 30%. This also observed experimentally. The simulation of the 25% loaded case exhibits the same unsteady flow as the experiments with the particles forming a characteristic distorted three pointed shape that flops around the inside of the mill with a tumbling motion spraying loose particles all around.

Power measurements were also made for the centrifugal mill with a fill level of 40% and a charge consisting of 4 kg of steel balls and 1 kg of quartz for a range of rotation rates. Matching DEM simulations were performed to determine the accuracy of the DEM predictions. The figure below shows the experimental, theoretical and DEM results for various rotation rates. The power predictions are all normalised by the mass of the charge to give specific power consumption, in order to enable direct comparison of these quantities. For most mill speeds multiple power measurements were made. They show a reasonable amount of variation. The spread in these results provides some idea of the amount of experimental error or variation that is intrinsic to these systems. The precise reasons for these variations are unknown.

For 300 rpm, the DEM prediction is extremely close to the single experimental result and is closer than the theoretical one. For the higher rotation rates (for which multiple experimental measurements were made) all the DEM predictions lie well within the experimental ranges. In general, they are near the middle of the ranges and for the 400-rpm case the DEM result is in the lower part of the range. One would expect the DEM predictions to be slightly lower than the true power consumption because mechanical energy losses in the motor and gears of the mill are not included in these predictions. The DEM power consumption is purely that consumed by the actual particle motions and their interactions with the mill chamber. It is also clear from this figure that the theoretical predictions of Hoyer (1985) represent an upper bound for the power, corresponding to the upper limit of the experimental range for each rotation rate. The DEM predictions are much closer to the mean experimental power for each rotation rate than are the theoretical values. This suggests that DEM is likely to give a good estimate of actual power draw and will predict this more accurately than does the theory.

This is one of the few applications for which we have been able to obtain high quality experimental data. The very close agreement between the simulations, the experiments and with the theory gives us a degree of confidence that the DEM approach of trying to model correctly the applications at the particle level is capturing sufficient reality to give good predictions. One important caveat is that the particles used in the experiments were very close to spherical and so the circular particles used to model them are a good approximation. Cases where the real particles are really non-circular are not always well matched by DEM simulations using circular particles. Flows such as in hoppers and in slowly rotating tumblers where the material is partially stationary and then must shear can be significantly affected by ignoring particle shape. More details regarding this application can be found in a paper by Cleary and Hoyer (2000).

Also, the CSIRO Minerals has been using the DEM to predict the three-dimension performance of the Hicom mill (Morton, 2003). As known, the Hicom mill has become a promising machine as an alternative for energy saving and effective size

reduction in ultrafine grinding of industrial minerals like calcite and dolomite. The detailed information on the simulation of the comminution in the Hicom mill is limited due to the commercial reasons at this moment.

5.3 Computer simulators

Computer simulation as a technique for design, optimisation and analysis of mineral processing operations like comminution has been developed since 1960's (King, 2001). Simulation is a procedure that can be utilised to model a comminution process (device and circuit) without actually running the experiments. The models, which are useful and effective in a simulator, must all fit seamlessly together so that the simulator can function in the intended way. Different models for the same unit operation must be interchangeable to facilitate their comparison under comparable operating conditions. The computer is an essential tool for simulation: In most systems, the individual unit operations are complex that the computer can be described in the mathematical terms only if these can be translated into computer code. In addition, the systems reveal complex interactions and interconnections among the individual units must be accurately accounted for. A simulator for processes is a set of computer programs that provides a detailed numerical description of the operation in a processing circuit. The simulator must be provided with an accurate description of the material (rock, ore or mineral) that is to be processed, a description of the flowsheet that defines the process and an accurate description of the operating behaviour of each unit operation that is included in the flowsheet. The simulator utilises these ingredients to provide a description of the operating plant. The detailed description of the material will include information on its physical and mineralogical characteristics. The flowsheet is the familiar graphical representation of the location of the unit operations in the plant together with the network of pipes and conveyors that transmit material between the units. The simulator links together the modelled behaviour of each unit operation and synthesises the overall performance of the circuit.

Metso Minerals Co.(formerly Nordberg) has developed a crushing plant simulator named BRUNO (Kaja, 2002). This simulator has been utilised to facilitate the comminution equipment selection process. The program was a DOS based mass balance program that kept track of the tonnage rate of each size fraction in various circuit flows. The Bruno uses a graphical environment to define the circuit components and their relationships. The pallet contains feed material, plant feeders and grizzly feeders, primary gyratory crushers, jaw crushers, cone crushers, impact crushers, screens, silos and stockpiles. The Bruno plant simulator is a tool for calculation of the capacity and gradation of crushing and screening circuit. It can provide an opportunity to vary circuit components and optimise the performance of a circuit and the equipment selection, resulting in a more cost-effective crushing solution.

According to Hedvall, *et al.* (2002), Sandvik Rock Processing AB, Sweden introduced a simulator PlantDesigner[®] for optimisation and design of crushing and screening plant circuits. This PlantDesigner[®] software is a PC program in Windows 98/ME or Windows 2000/XP for design of flowsheets, simulation of processes and calculation of mass balances for crushing and screening plants. The programming language is a structured subset of C with object-oriented extensions. Figure 63 shows how the

PlantDesigner[®] interacts with starting and final properties. It was reported (Hedvall, *et al.*, 2002) that in order to obtain good results predicted with the PlantDesigner[®], the company has more than 12000 tests for various materials with the machines/equipment in the PlantDesigner[®] database. This engineering tool can predict and calculate new applications/processes with a high accuracy.

A simulator for analysis, optimisation and design of comminution circuits so-called JKSimMet has been developed by the Julius Kruttschnitt Mineral Research Centre (JKMRC), Australia (Morrison, *et al.*, 2002). The JKSimMet is a recognition of the need to integrate certain fundamental tasks in one piece of software. The tasks that have considerable synergy with one another include flowsheet drawing, data analysis, model fitting, simulation and reporting. These tasks are integral to the iterative nature of the simulation process. This software or simulator is a user-friendly package for processing engineers. The current version 5 of JKSimMet incorporates all of the essential tasks. This is designed for use with Windows/MS. The graphical user interface of JKSimMet communicates with a Microsoft Access database that stores and organises the user's data by projects and flowsheets within a project. This software contains an extensive library of unit models for use in all three major functions of data analysis, model fitting and simulation. The user needs only to specify which unit models are required for the current flowsheet case, connect them with flowstreams and to specify the necessary design variables, which define the current or starting operating condition for each unit. Flowstreams are also models in this software. Streams are modelled by specifying total flows of solids and liquids, as well as solid phase and characteristics (such as specific gravity). The JKSimMet has been regarded to be a steady-state process simulator for data analysis, plant optimisation and plant design for comminution and classification circuit.

The USIM PAC simulator for design/optimisation of mineral processing plant has been developed for 16 years by BRGM, France (Brochot, *et al.*, 2002). The latest version available is the USIM PAC 3.0, which incorporates the modern developments. This is a user-friendly steady-state simulator that allows processing engineers and researchers to model plant operations with available experimental data and determine optimal plant configuration that meets production targets. The simulator can also assist plant designers with sizing unit operations required to achieve given circuit objectives. Figures 64-66 show the methodologies used to produce a preliminary plant design, to design an industrial plant from a pilot plant campaign, and to optimise an existing plant, respectively.

The University of Utah, USA (King, 2001), has developed a simulator MODSIM. The simulator offers the versatility to the user to modify and adapt the models of the unit operations that are used. The underlying theme for the models that are used in the MODSIM is the population balance method. In addition to the application in engineering, the MODSIM has been used as an academic tool to enhance the educational experience of students of mineral processing. Figure 67 shows the closed milling circuit with a rod mill, a ball mill and hydrocyclones. The simulated size distributions around the circuit are given in Figure 68.

Herbst and Nordell (2002) recently introduced a new methodology so called high fidelity simulation (HFS) for simulation of comminution devices. The HFS tools of values for processing design include discrete element modelling (DEM),

computational fluid dynamics (CFD), discrete grain breakage (DGB) and population balance modelling (PEM). They used the HFS tools to accurately predict the scale-up calculation of a ball mill, milling performance of SAG mills, breakage behaviour for primary crushing, and screening performance as well. For instance, in order to examine the accuracy of HFS scale-up calculations for ball mills, a batch mill grinding test was conducted with an iron ore concentrate below 10 mesh in a lab-scale ball mill. Also, a DEM simulation for the lab-scale tests was carried out for the same conditions used in the experiments. Figure 69 shows the estimated micro-scale breakage rate parameters from the experimental data and the DEM energy spectra. They calculated a macro-scale selection functions, which were in turn used to perform the PBM simulations for a large 13.5×26 ft ball mill, with the predicted impact energy dissipation and the estimated micro-scale parameters. The results are shown in Figure 70. It is seen that the product size distribution is accurately predicted by this procedure. The power draw and feed rate predicted of 1999 kW and 106 MTPH are very close to the measured values of 2004 kW and 106 MTPH, respectively.

Mine-to-mill exists on a number of levels ranging from enterprise simulation to exploring for the best combination of comminution processes (blasting-crushing-grinding). The simulator can then mimic the real circuit performance. However, application of a simulator for a comminution chain from mine-to-mill is sparse except some recent work by the JKMRC (Morrison, *et al.*, 2002) and Herbst, *et al.* (2000 and 2001). The main objective for use of a simulator in the chain should be to reduce energy consumption without reducing the throughput and operating efficiency.

The JKMRC, Australia has developed a combined software package for optimisation of mine-to-mill comminution circuit. Perhaps the most profitable of all optimisation possibilities has been the matching of run of mine sizing to milling circuit characteristics. The JKSimMet simulation program combined with another program JKSimBlast can be used to optimise, control and analyse the whole comminution chain from mine-to-mill. The JKSimBlast is used to estimate the product size distribution from blasting. Two successful examples can be referenced (Kanchibotla, *et al.*, 1998; Kojovic, *et al.*, 1998). A work by Kanchibotla, *et al.* aimed to maximise the throughput and Kojovic, *et al.* tried to minimise to production of < 6 mm iron ore. The models used in the both softwares in collaboration with the client can investigate blasting and milling scenarios to predict the operating conditions that provide maximum comminution efficiency and minimum cost.

Herbst and Blust (2000) utilised the PBM in their software named MinOcad to study mine-to-mill optimisation. In the case, the plant is required to treat four distinct ore types with different hardnesses, and the question was what the blending strategy would yield the best performance, assuming the crushing and grinding circuits were controlled to maximise production regardless of the feeds. The simulation software by Herbst, *et al.* (2001) employed a multi-component approach and energy-based comminution models, where the latter make it possible to look at tradeoffs between finer fragmentation in blasting to changes in gyratory crusher settlings and SAG mill operation. In their study, numerous alternatives were investigated. The results in Table 5 show that best blending strategy would be to mix all ore types in the proportion they exist in the mine, and run with a more open gyratory crusher setting (OSS). Evidently, altering the run of mine size by changing powder factor (PF) has little effect. From an operating perspective the important points are to maximise

blending prior to the crushing process, and to ensure there is sufficient coarse material in the SAG feed to provide maximum rates of breakage.

Table 5 Simulated results

	Ore feedrate, MTPH	Total energy, kWh/MT
Option 1: four ores crushed/ground separately (PF =0.177 kg/MT and OSS=200 mm)	285	18.7
Option 2: Four ores blended at crusher (PF =0.177 kg/MT)		
OSS=150 mm	287	18.6
OSS=175 mm	312	17.1
OSS=200 mm	326	16.4
OSS=225 mm	334	16.0
Option 3: Four ores blended at crusher (OSS=200 mm)		
PF=0.200 kg/MT	326	16.5
PF=0.177 kg/MT	326	16.4
PF=0.100 kg/MT	326	16.3

6 Summary and outlook

The recent mill developments have been brought forward to the manufacture of equipment, which is based on either high-pressure inter-particles bed comminution or on small grinding media intensively stirred, in combination with either vibration or eccentric actions. Some of the mills have been designed according to the combined actions of attrition and compression. The developed mills have been replacing the conventional ball mills for the production of fine particles.

Besides the energy saving, the HPRM offers a selective liberation of valuable minerals within the ores. The POITTEMILL eliminates the high-compaction flakes and agglomerates due to its specific pulsated pressure action during the process. The HOROMILL is one of the specific designs of the roller press. A comparison of the performances of these rollers is suggested.

Small media grinding innovations include agitated bead mills, as opposed to the more traditional stirred ball mills and ball mills. The stirred media mills like the SAM, IsaMill, MaxxMill, ATR-MILL ANI-Metprotech Mill and KD-mill at present have higher energy intensities than conventional mills and can avoid the consequent problems of media separation from the final product for mills in continuous use. Power savings are achieved by the ability of the mills to stir the very small media necessary for efficient fine grinding. Some aspects on recent developments of high-efficiency stirred media mills mainly involve a) use of smallest grinding beads down to 0.10 mm for superfine particle production; b) new designs for separation of small grinding beads from the ground product; and c) application of additional force fields such as centrifugation and vibration. These developments make the mechanical production of colloidal brittle particles in nano-scale possible.

In addition, there are other types of high-efficiency mills associated with vibration and eccentric, impact and centrifugal actions such as the VKE and eccentric vibration mill, Centrifugal mills and jetmills. The Hicom Mill is of a unique design, which can selectively liberate valuable particles (e.g., diamond) within the ores. All of these mill types are available for wet and/or dry fine and ultra-fine grinding. These mills reduce the specific energy consumption and improve the product quality. Depending on the grinding mechanism employed in a particular equipment, limitations exist for achieving final size of ground products. Variables of the milling process like media type, size and density, type of movement of media, ratio of maximum particle size to media size, etc., play an important role in determining the efficiency of fine particle production. Selective liberation of valuable particles within the ores is one advantage in the application of some new or improved mills.

Utilisation of chemical, or thermal or ultrasonic energies to the fine grinding process has been a viable avenue of exploration and research. These assisted-techniques have a significant impact on the improvement of the performance and the achievement of lower energy consumption in a comminution process. Chemicals used as grinding aids in fine grinding processes generally increase grinding energy efficiency, bring down the limit of grinding, prevent the agglomerates or aggregates of ground particles, avoid grinding media coating and improve the rheology of material flow as well. Thermal stress fractures in microwave energy assisted comminution are induced along the grain boundaries between the different minerals as a result of the difference in the absorption behaviours and the thermal expansion coefficients of the materials. Microwave energy can reduce the work index of the certain materials, which favours the subsequent grinding for efficient size reduction, mineral liberation and energy saving. The microwave assisted comminution is a promising technology for the liberation of the precious metals (gold) in the ore matrix. Also, a better breakage behaviour of a grinding device like HPRM can be achieved with an assistance of ultrasonic activation. The active roller with a high-efficiency ultrasonic vibrator piezo-electrically driven has been designed to obtain a low energy consumption required in comminution.

Particle classification with new and improved classifiers (air classifier and centrifuges) from the processes can save energy, avoid over-grinding, improve the product quality and increase the unit capacity. Some new air classifiers (V-/VSK separator, Inprosyst and Turboplex with a new wheel) have applied to various fine comminution processes in order to saving energy for the required product quality. Recent work has been challenged to produce very fine particles with a narrow size distribution efficiently. This has reflected both in effective application of the improved classifiers (Centrisizer and disc-stack nozzle centrifuges) and in development of new centrifuges (TU Clausthal centrifuge and Counter-flow rotating hydro-classifier). Centrifuges have emerged to efficiently achieve a product with a cut size of 0.2-1.0 μm . The product size distribution becomes steeper and finer after removal of the undesired coarse particles in the feed. These centrifuges have been used in some commercial flow sheets to produce a very fine powder. Obviously, further developments will extend the achieved limits and lead to the design of new centrifuges.

It has been demonstrated that the commercially available instruments for on-line/in-line analysis and control of particle size are suitable for use in obtaining particle size

distributions by means of laser diffraction or ultrasonic extinction or image analysis, even with fine powders. The instruments based on either laser diffraction or ultrasonic extinction can be used for fine particles down to 0.1 or 0.5 μm . The image analysis technique is used for on-line measurement of relatively coarser particles. These instruments have been recently installed in various industrial lines for production of fine powders in order to control the product quality and reduce the whole energy cost. However, the precision/accuracy of the on-line or in-line particle size analysis instruments for secure industrial installation and application should be further improved. To ensure the reliable results it is necessary to compare the results from the on-line/in-line instruments with the off-line analysis. In addition, acoustic emission soft-sensors have been applied for control and optimisation of a tumbling ball mill performance. With the development of the advanced instruments, the more on-line systems for control and optimisation of grinding processes will be most likely installed.

Model developments on modern mills like stirred media mills (tower mills), high-pressure roller mills (HPRM), centrifugal mills and Hicom mill have received some attention. Methodology for the models involves empirical derivation method, population balance method (PBM), discrete element method (DEM) and computational fluid dynamics models (CFD). Their combination used for simulators and softwares, especially PBM with DEM and/or CFD, becomes of particular interests to industrial applications, and will be a major concern for the simulation of “real case” in the near future. The models for power draw, product size distribution and throughput in the HPRM with various surface geometries (smooth and studded) have been applied for the simulation from lab- to full-scale machines. Efforts to model and simulate the size reduction and power draw of tower mill (vertical stirred mills) have been put for the scale-up purpose. The population balance model with tracer technology has been used to predict the performance (size reduction and residence time distribution) of the stirred mills. The present CFD modelling for the horizontal stirred mills provide some information regarding the flow pattern, velocities and shear rate with the mill. This model also predicts the power draw, residence time distribution and wear in the mill. However, the CFD method for simulation of the grinding performance of the stirred mills is still needed to be further developed. The DEM has been used to simulate the 2-D performance of the wear and grinding beads with various geometries in the horizontal stirred mill. The 3-D simulation of the milling performance of the stirred mill with the DEM will be highly expected in the near future. The simulation with DEM for centrifugal mills and Hicom mill has been also developed.

The existing simulators developed can be used as an engineering tool in steady-state process simulation for data analysis, plant optimisation and plant design. Most of these software packages are run on PC under Window environments and user-friendly. Some simulators like USIM PAC 3.0 offer a wide spectrum of design criteria such as comminution process optimisation in industry.

Possible investigations involve the optimisation of blasting for downstream, simulation of fragmentation by blasting and comminution using the existing software and use of advanced image technology into analysis of fragment size distribution. Blasting design should deal with the economic optimisation by balancing energy utilisation of blasting and subsequent comminution. An increase of applied explosive

energy will lead to finer fragmentation and a larger number of micro-cracks in the primary fragments, which can be beneficial to the subsequent crushing and grinding. Finer fragmentation can give a higher productivity, less wear and less maintenance for loading, hauling and primary crushing. The increased explosive energy will, however, necessitate higher costs for drilling and blasting. Therefore, the optimisation of blast design must be based on either minimisation of production costs or maximisation of operating profits. In practice, the optimisation of blast design is difficult because the blasting operation on site will seldom give consistent results from one blast to the next. The variations of rock conditions, which always affect the result are another reason for the difficulties. The most common problem experienced involves very real differences between designed and practical blasting operations. The simulation of different energy chains with the existing softwares is possible for the optimisation purpose. It has been found that there is a balance between fragmentation by blasting and subsequent comminution in energy utilisation and production cost. These different operations have their respective mode of operation in various ways. Experiments for establishment of the optimum point for the balance are costly and difficult. Therefore, it is proposed to use the existing simulators named JKSimBlast/JKSimMet and the MinOocad to analyse and optimise the comminution chain from mine-to-mill in order to reduce energy consumption without decreasing the throughput and operating efficiency. In addition, development of models for fragmentation in open pit and underground blasting is needed. Digital image analysis for fragment size distributions obtained by blasting and crushing. Quantitative determination of massive blasted materials in field blasting tests is rather difficult. Advanced image analysis technology provides an approach to solve this problem.

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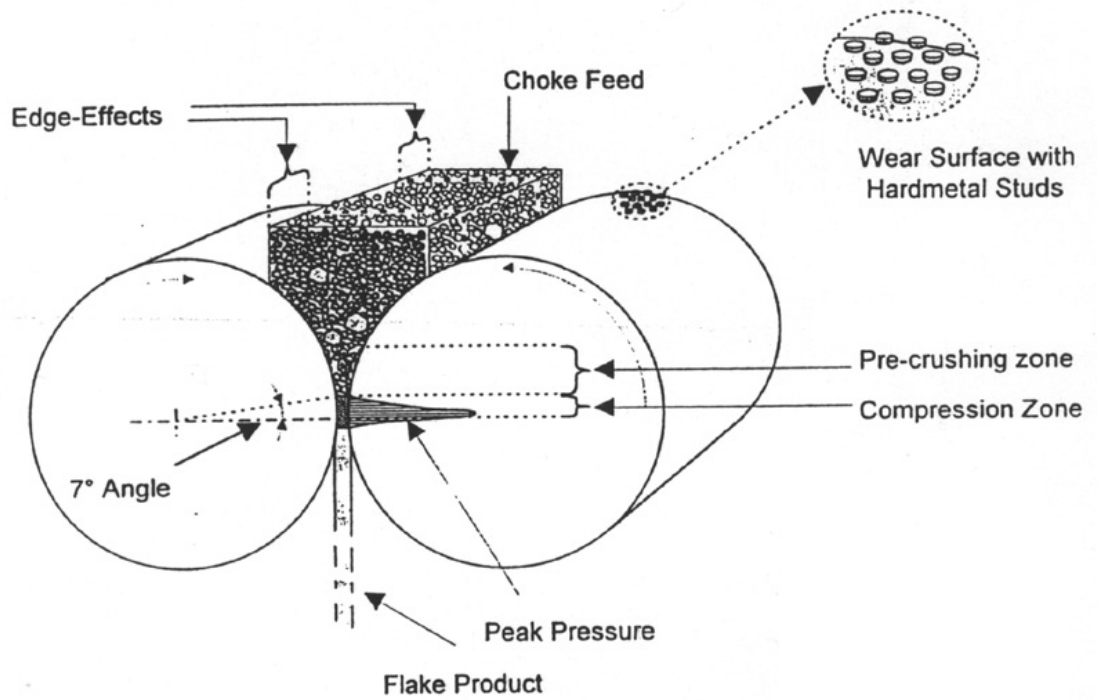


Figure 1

% Reduction in BM Grindability

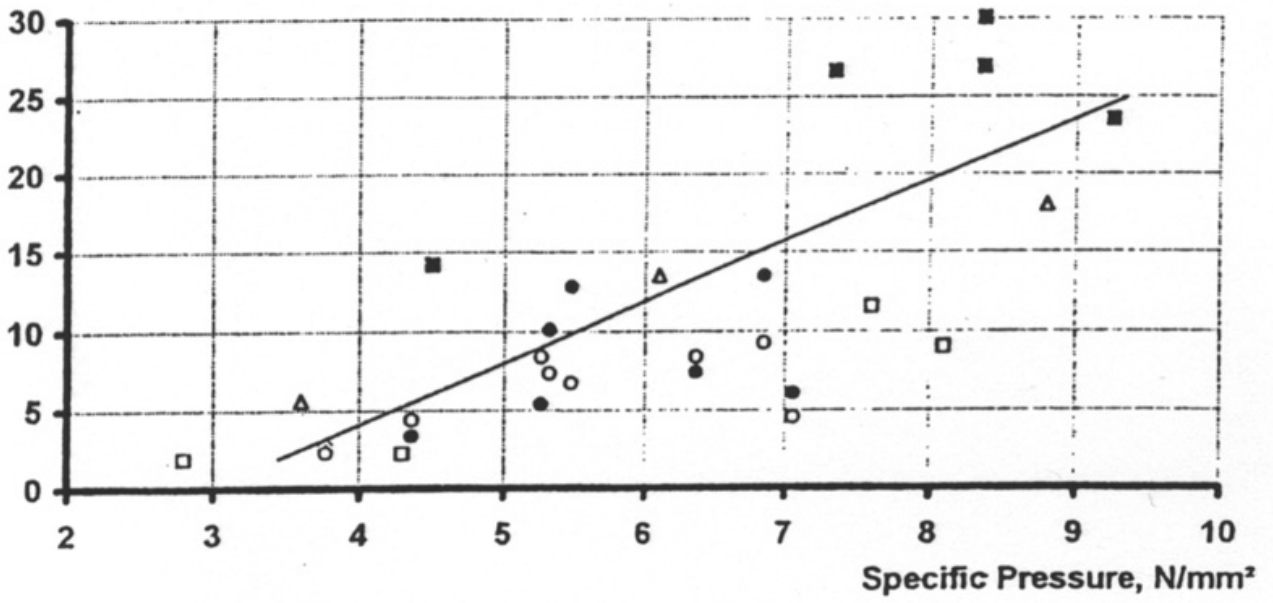


Figure 2

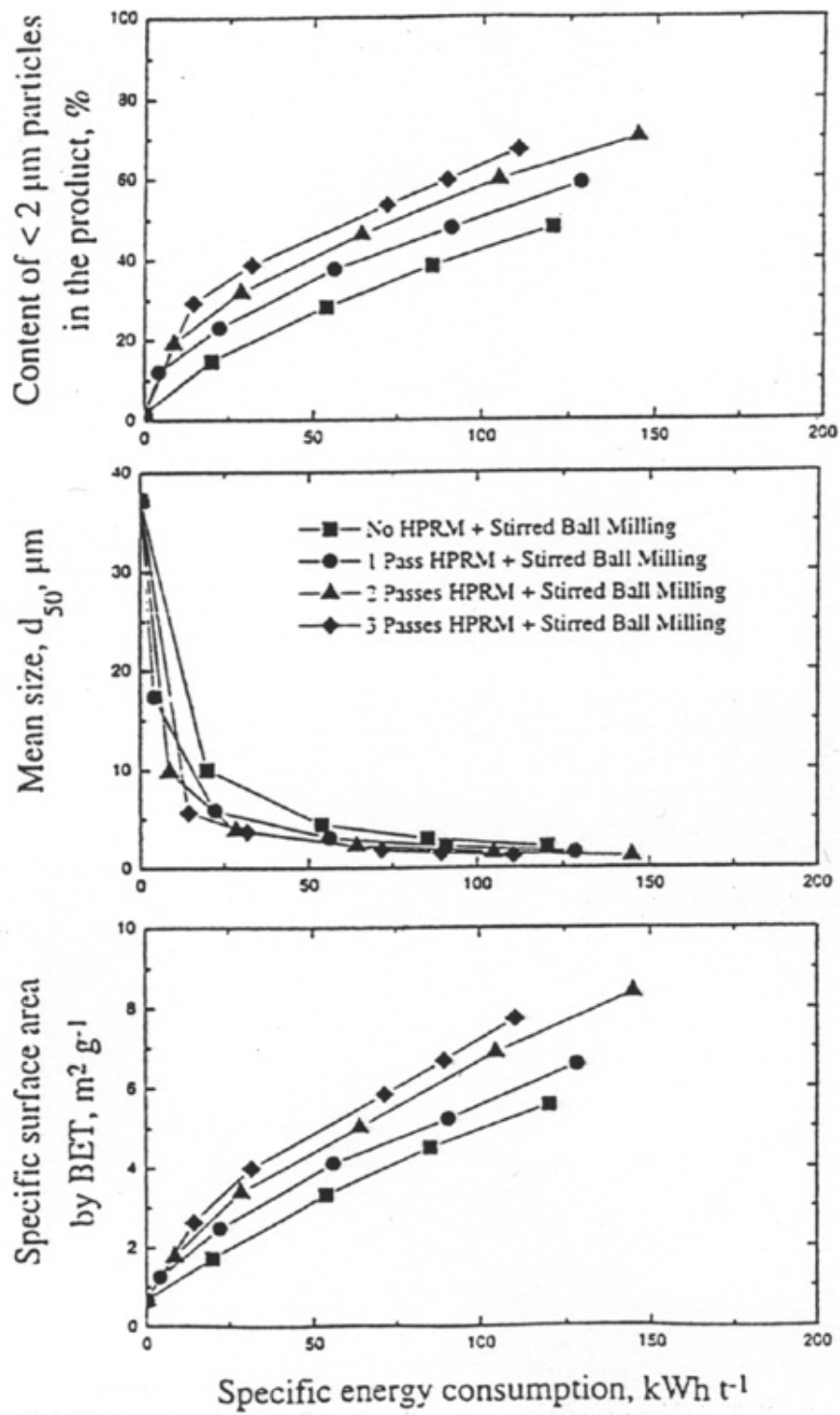


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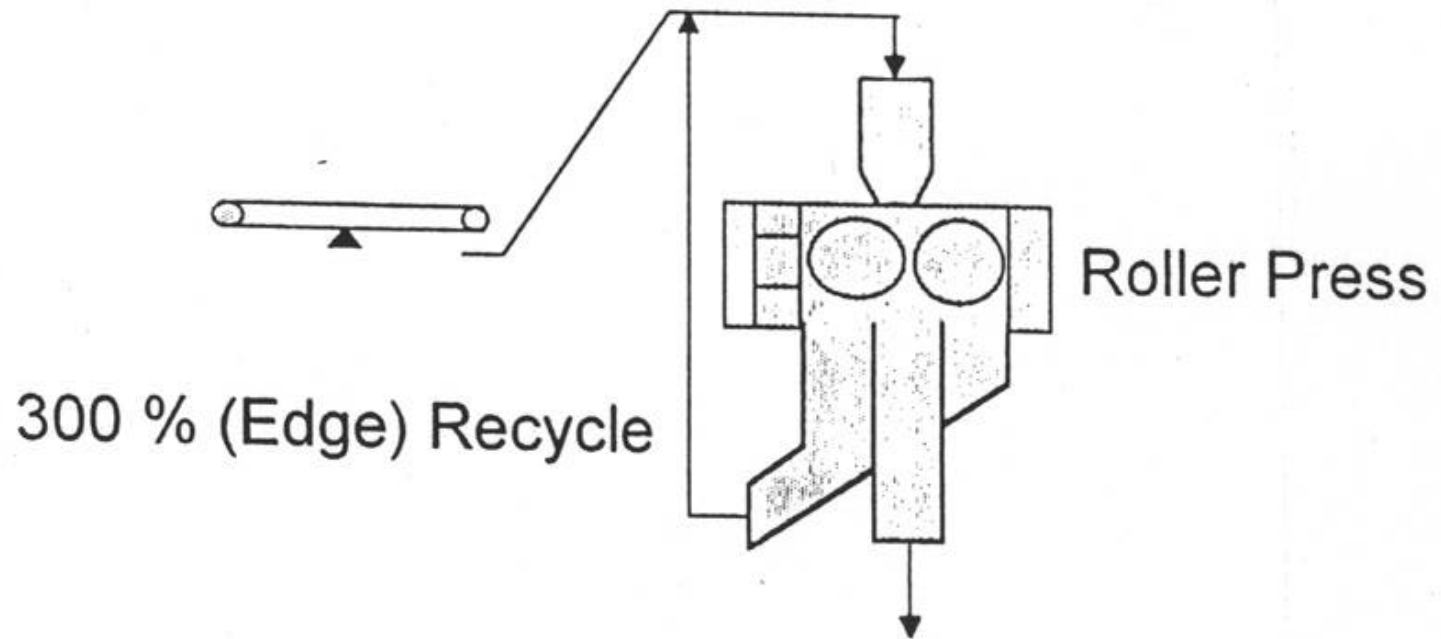


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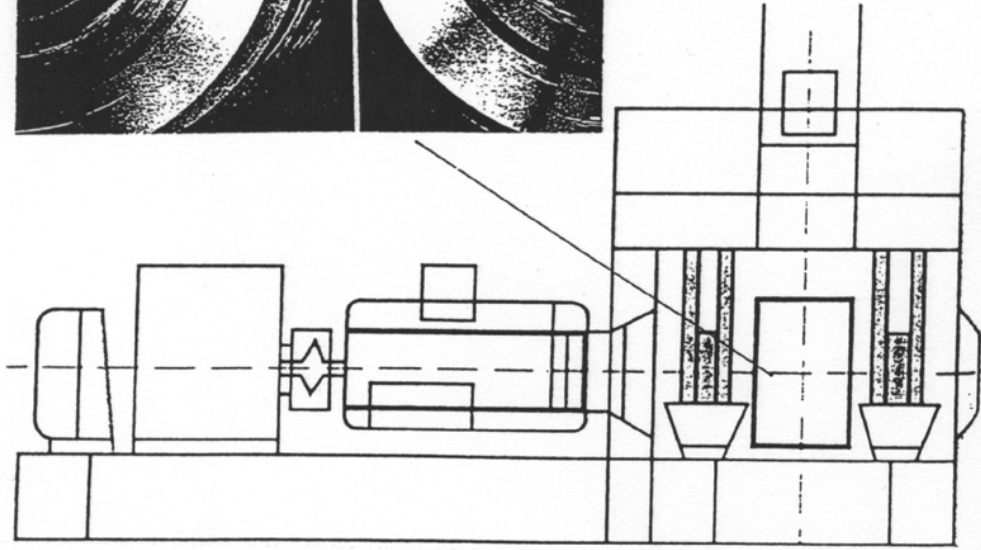
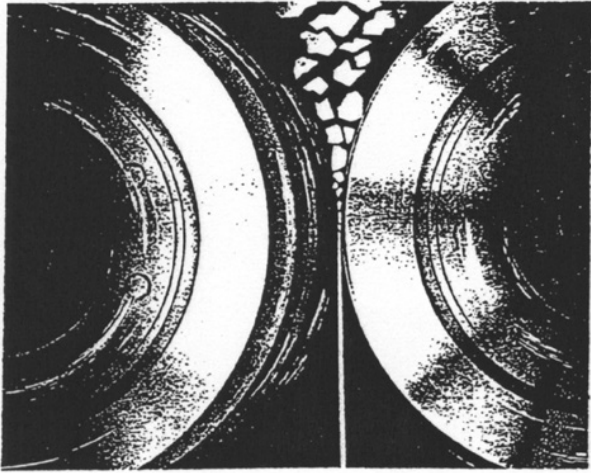


Figure 5

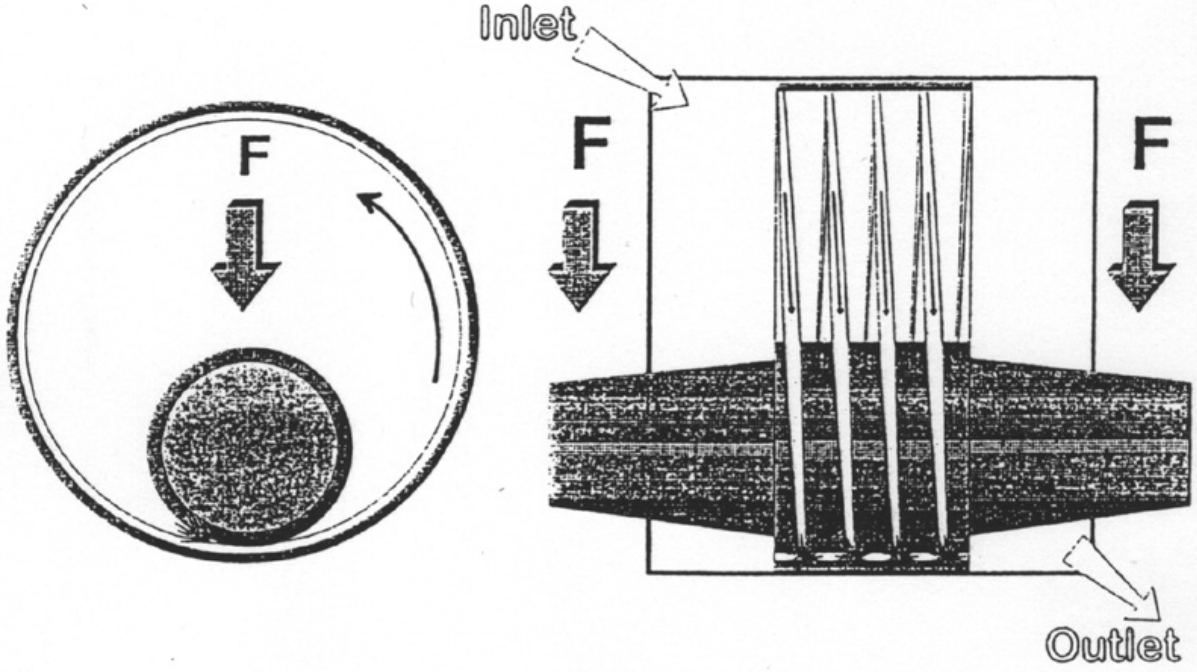


Figure 6

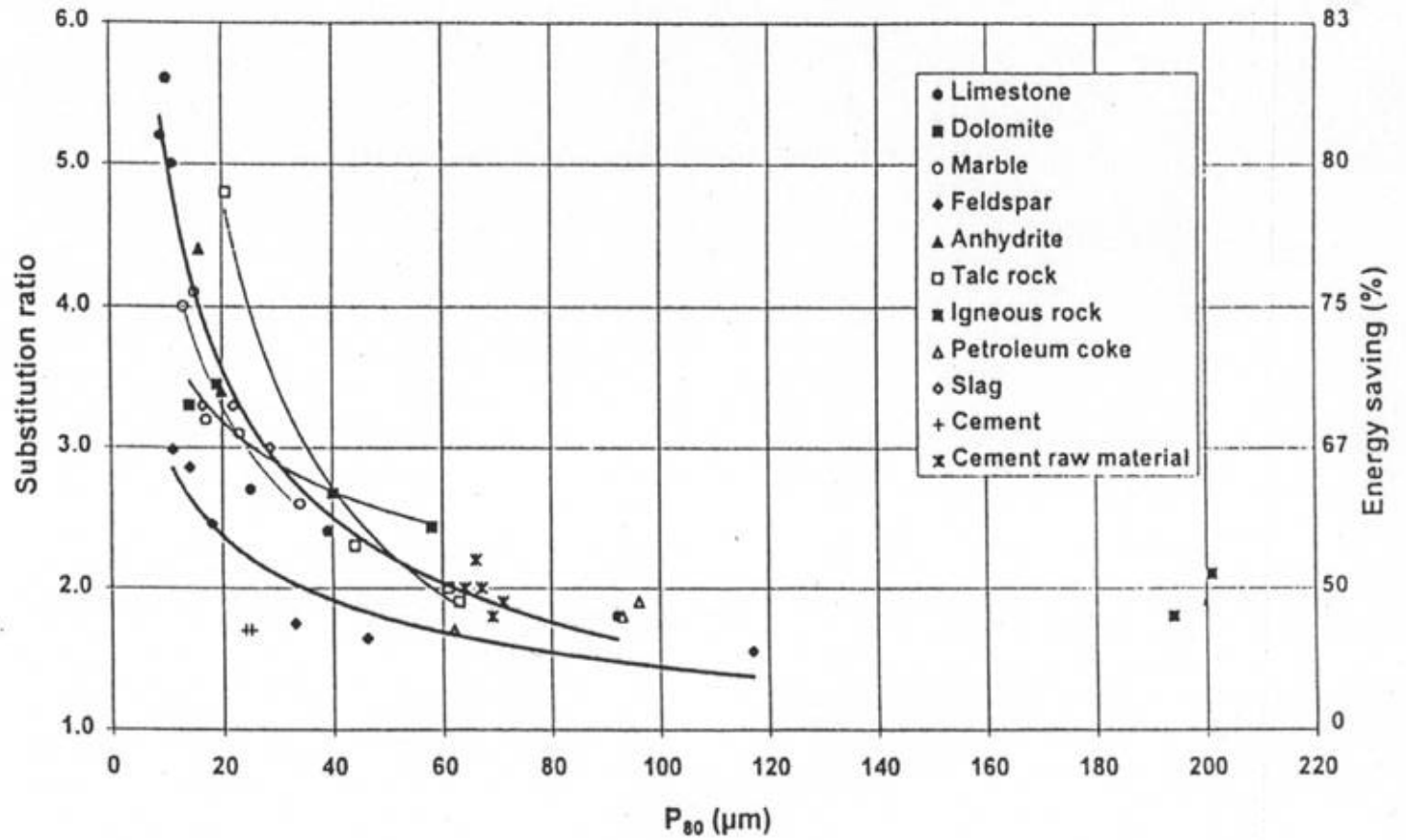
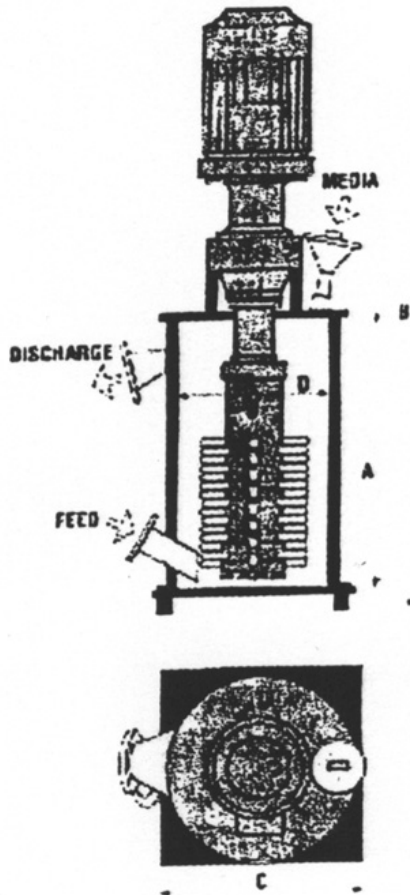


Figure 7

Wet mode



Dry mode

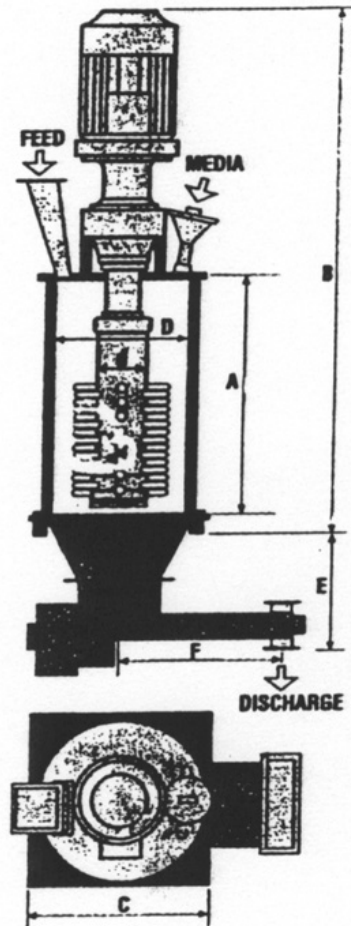


Figure 8

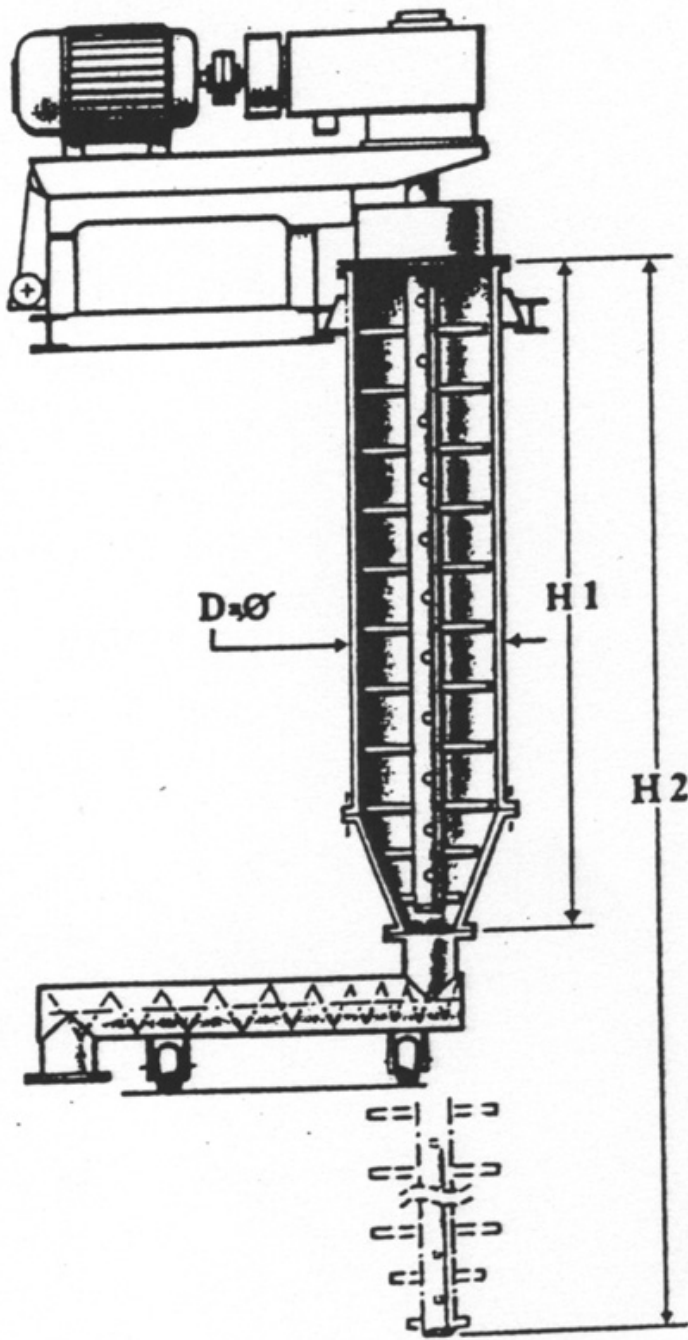


Figure 9

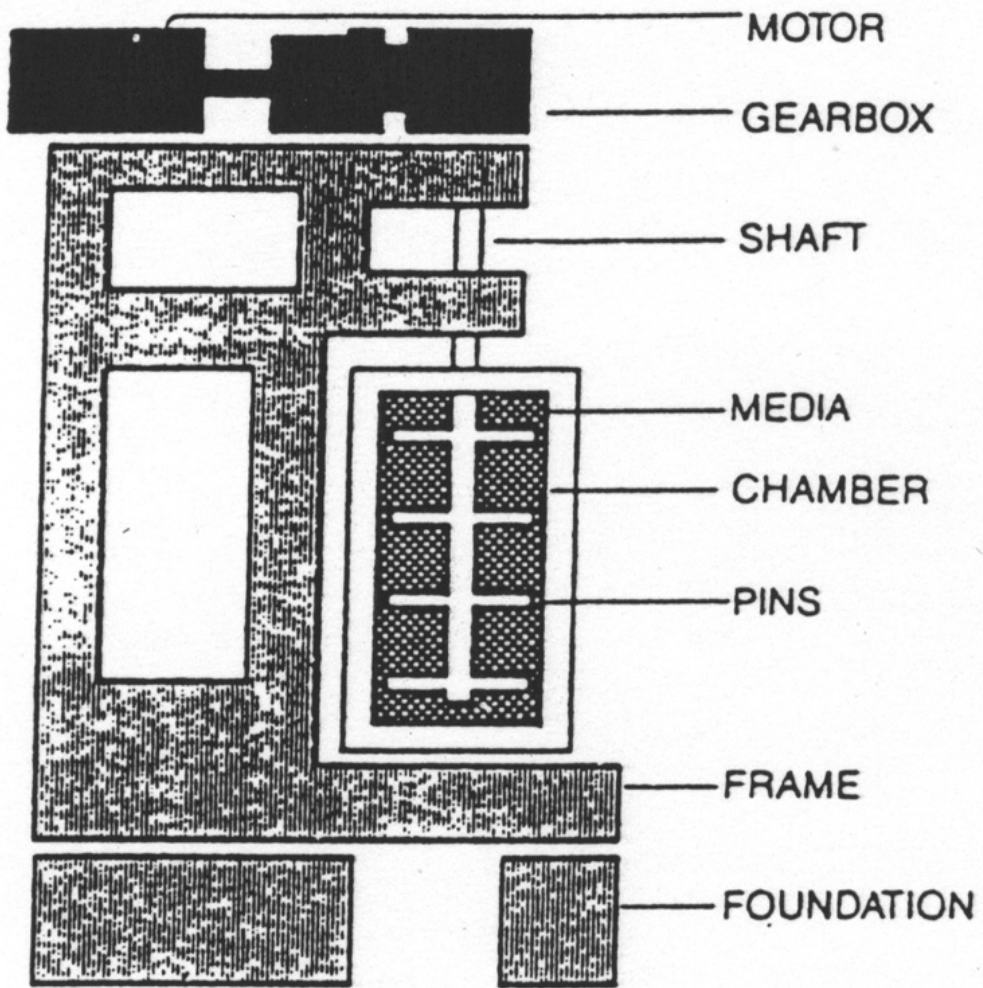


Figure 10

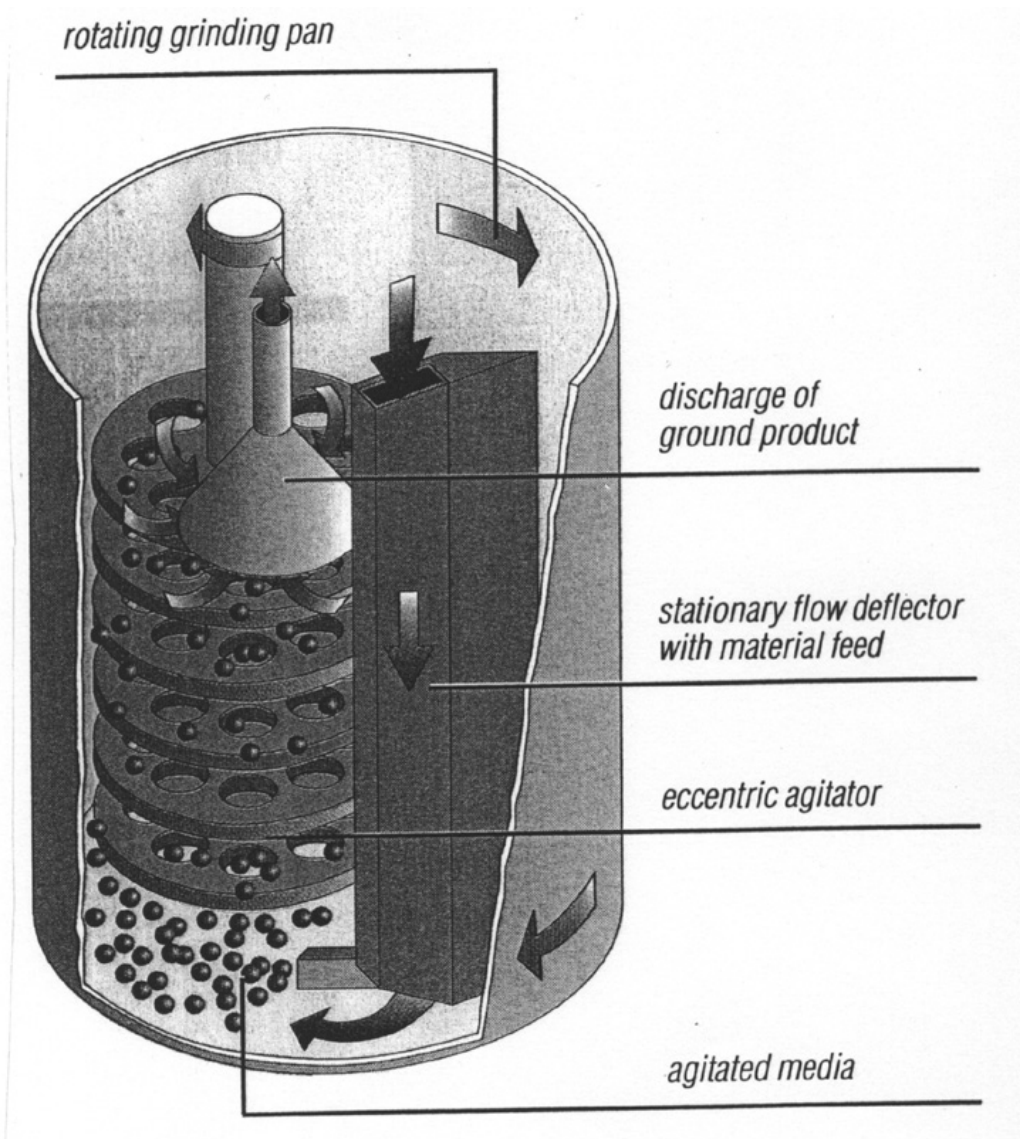


Figure 11

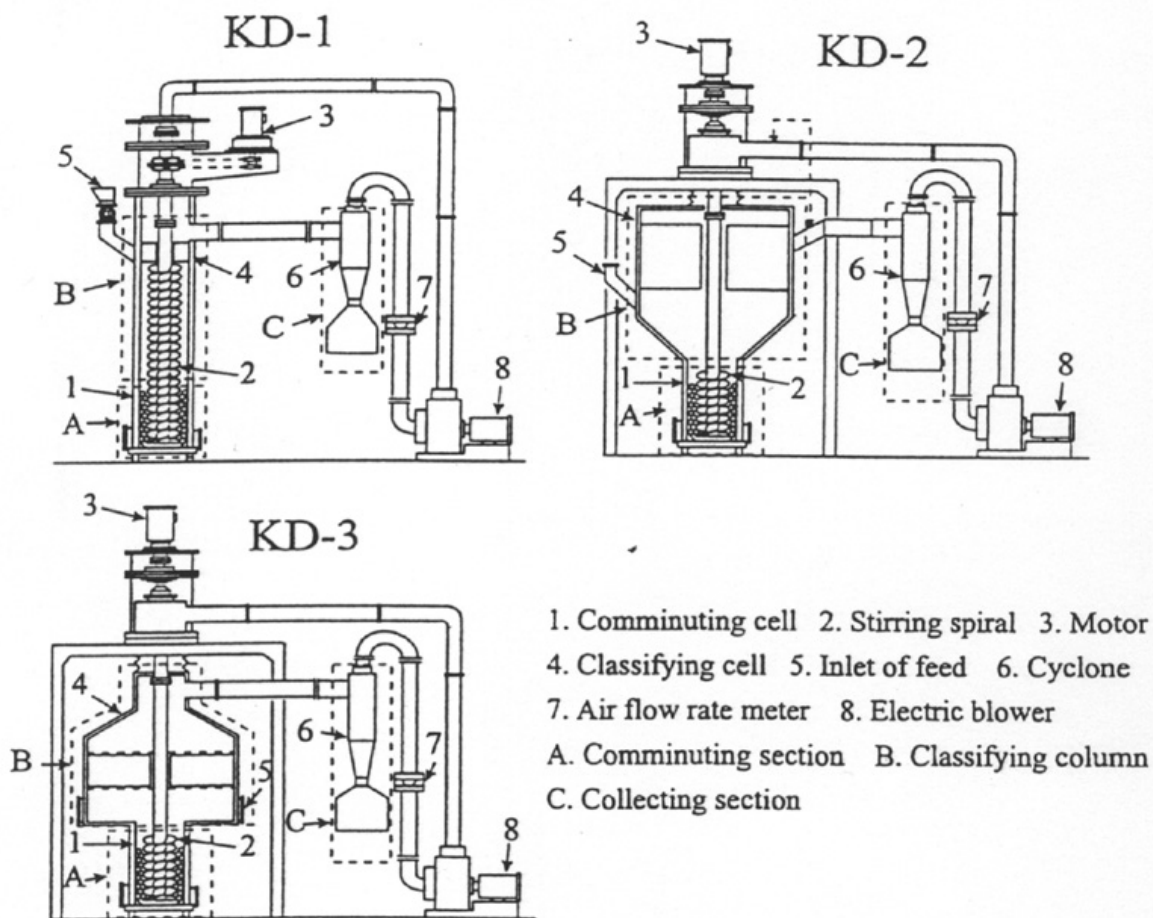


Figure 12

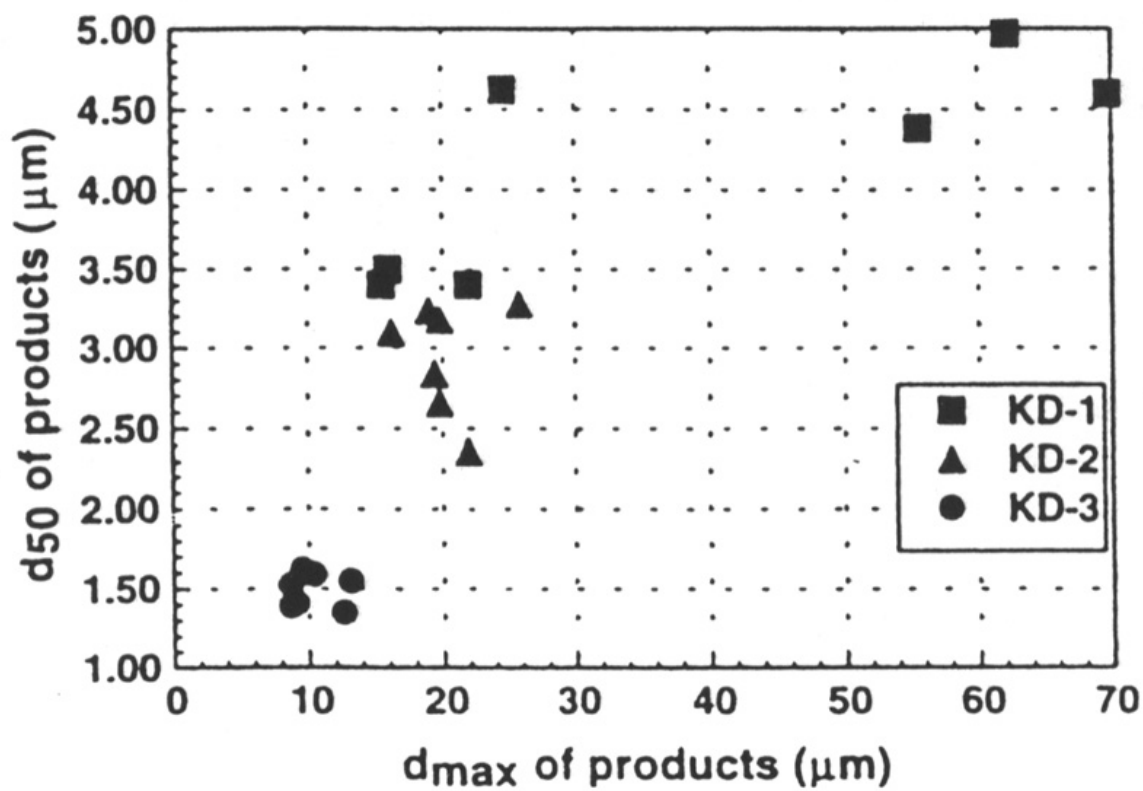


Figure 13

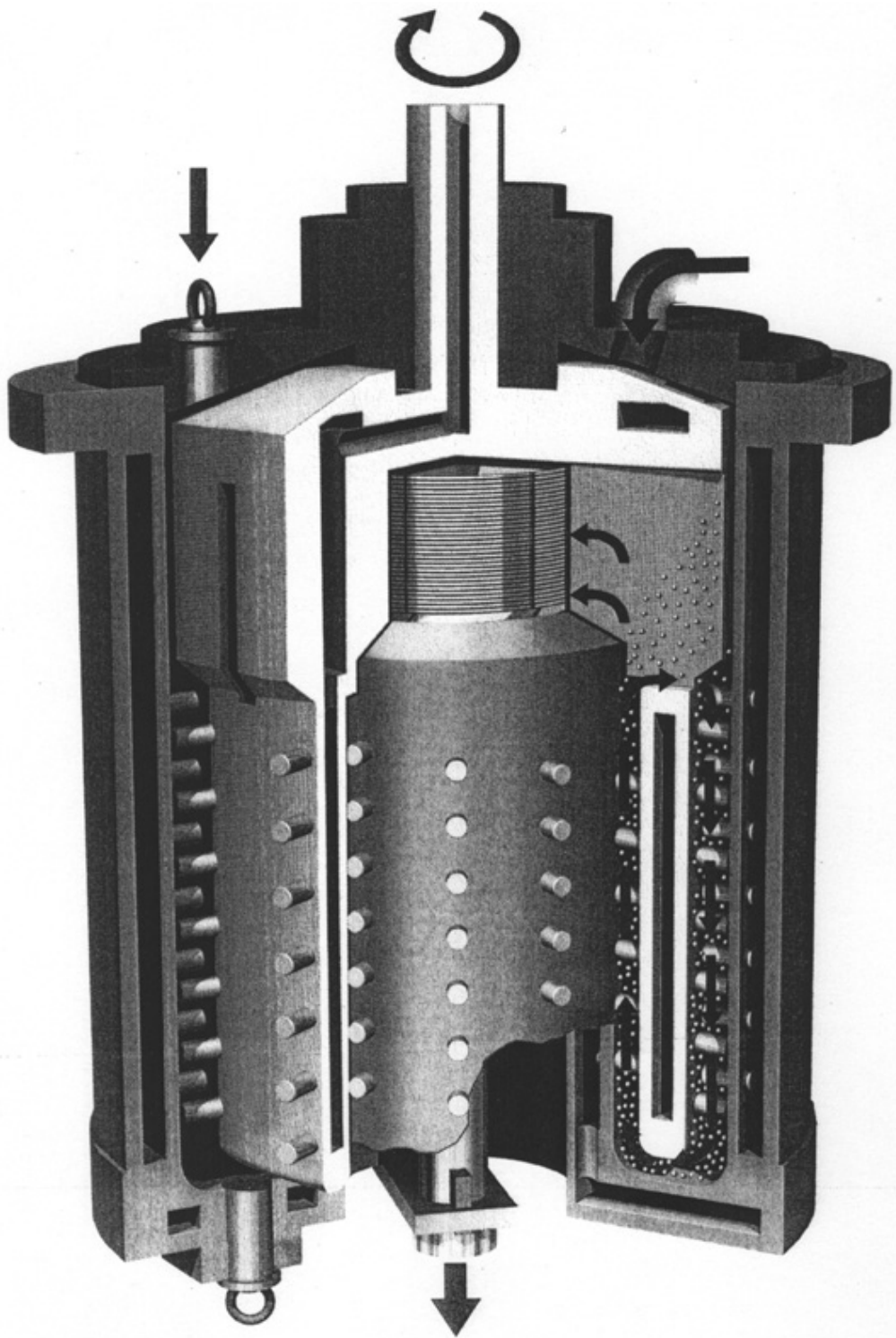


Figure 14

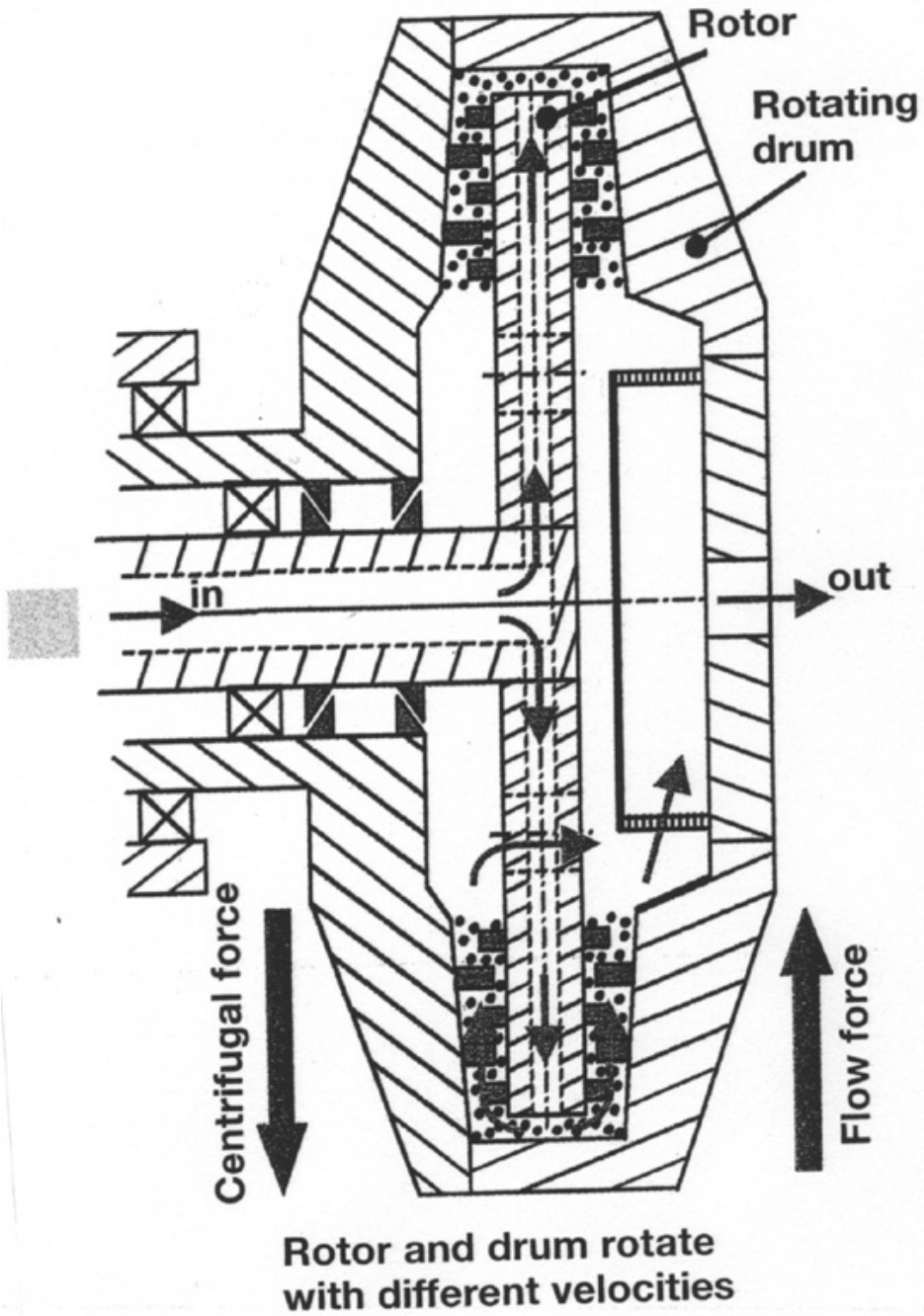


Figure 15

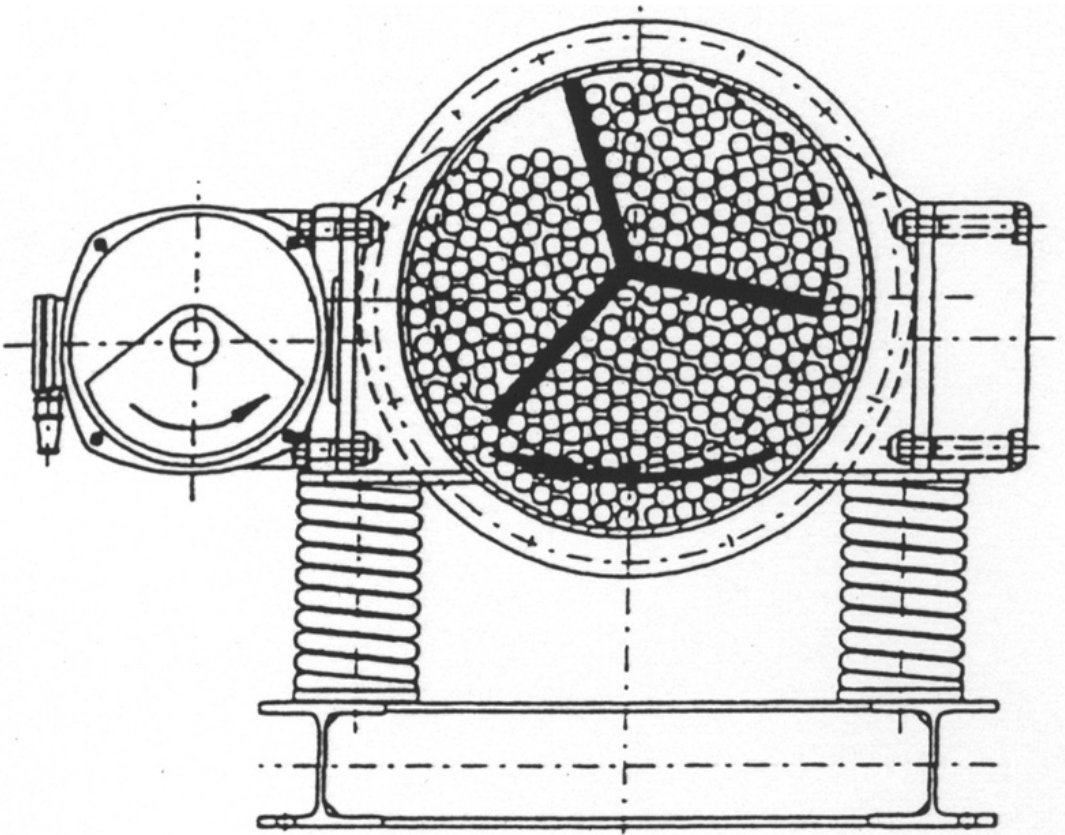


Figure 16

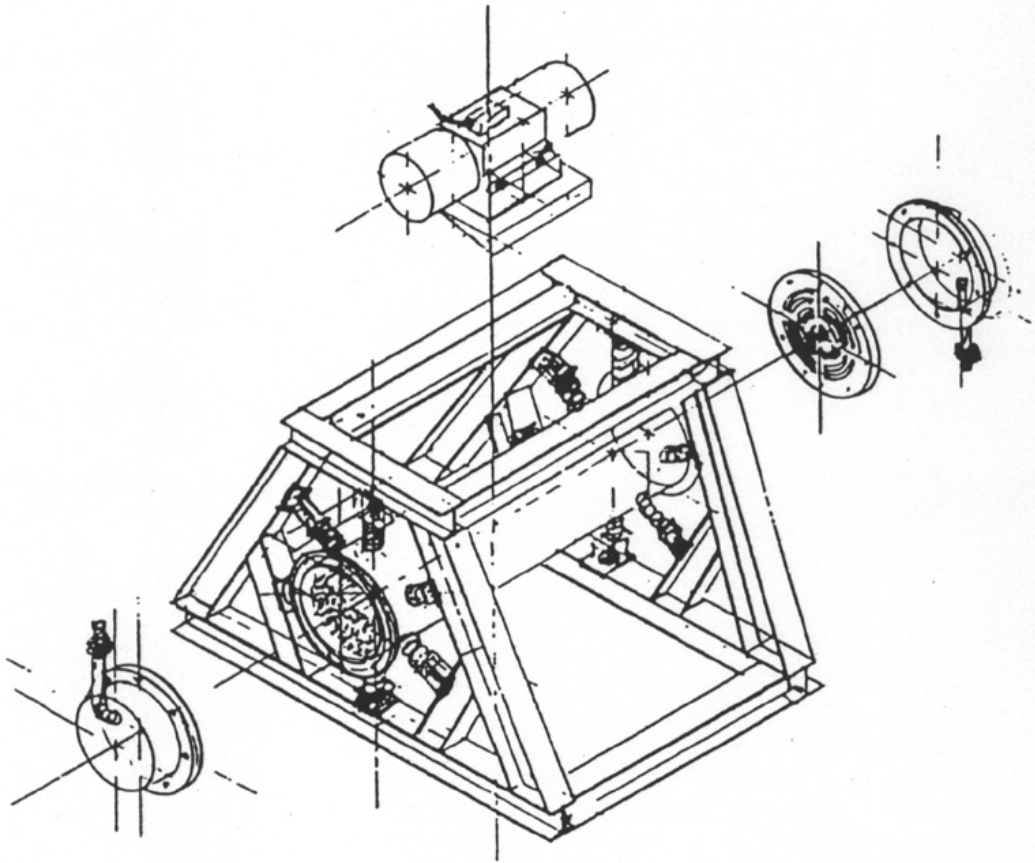


Figure 17

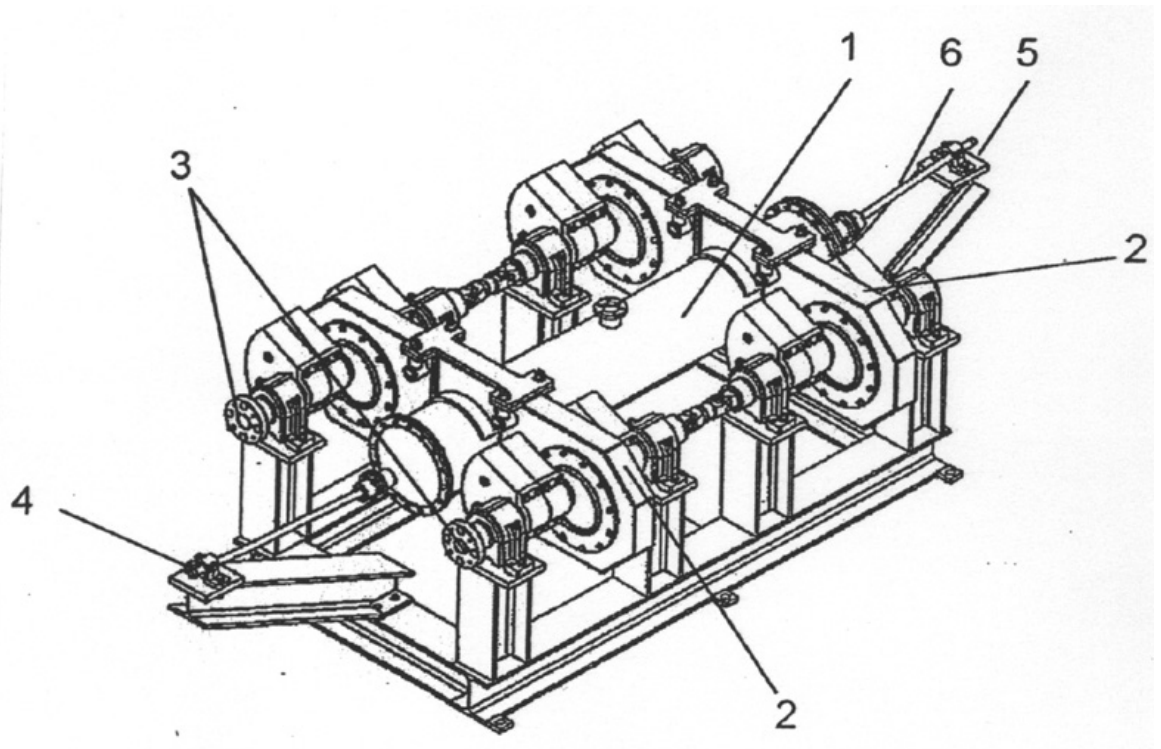


Figure 18

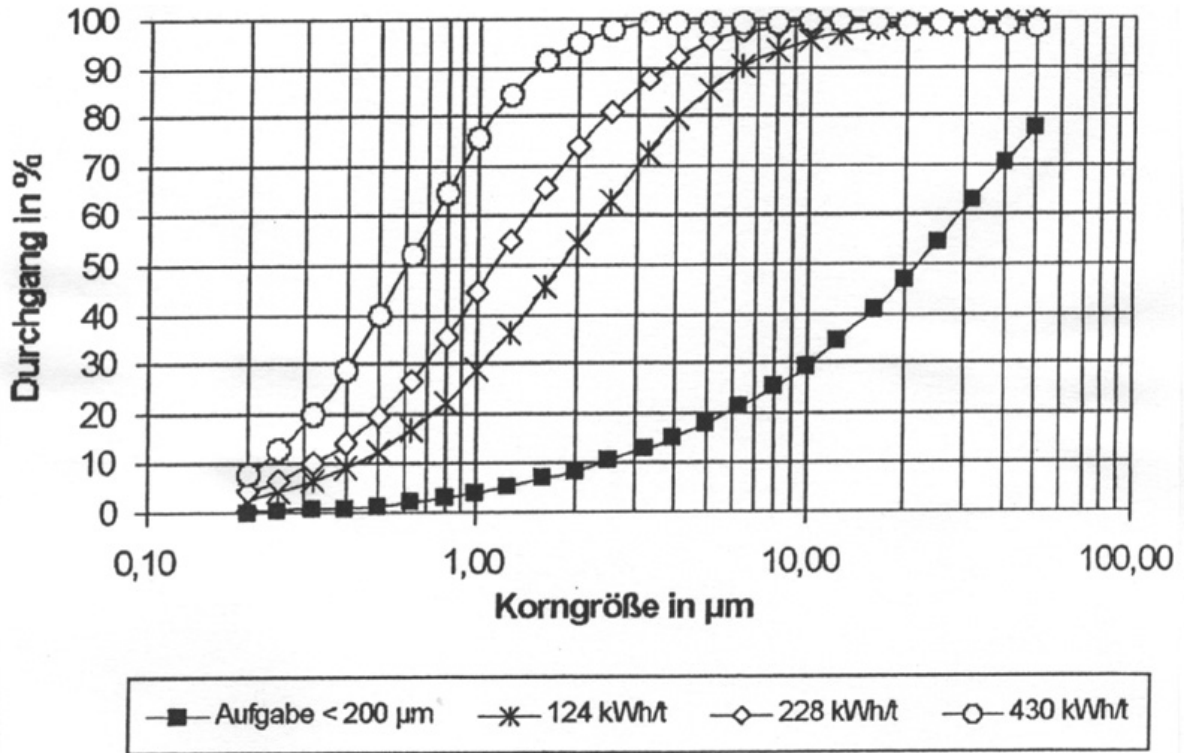
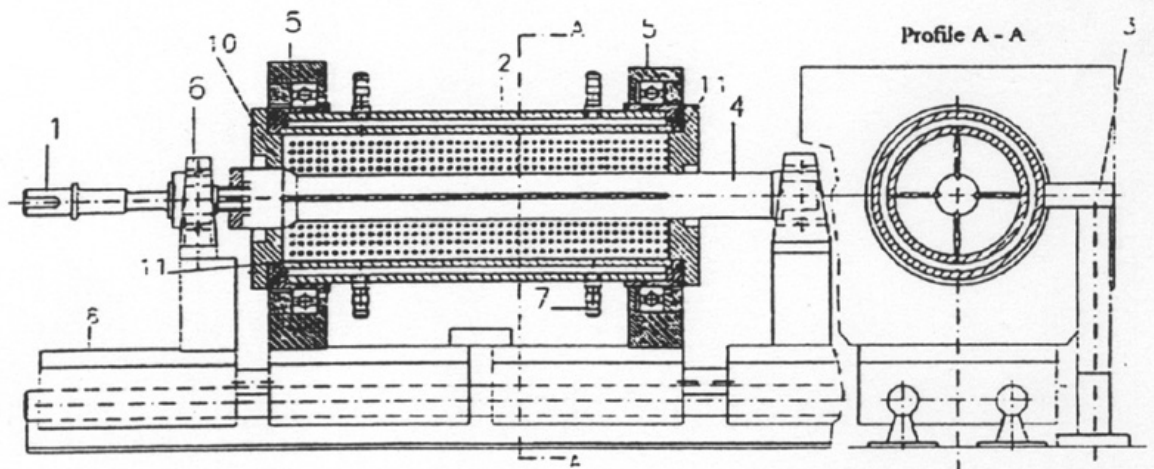


Figure 19



- | | | | |
|----|------------------------------|----|-------------------|
| 1 | torquemeter | 2 | milling chamber |
| 3 | extension arm | 4 | rotor shaft |
| 5 | bearing casing | 6 | pedestral bearing |
| 7 | cooling water in- and outlet | 8 | slide casing |
| 10 | rotary seal | 11 | chamber lid |

Figure 20

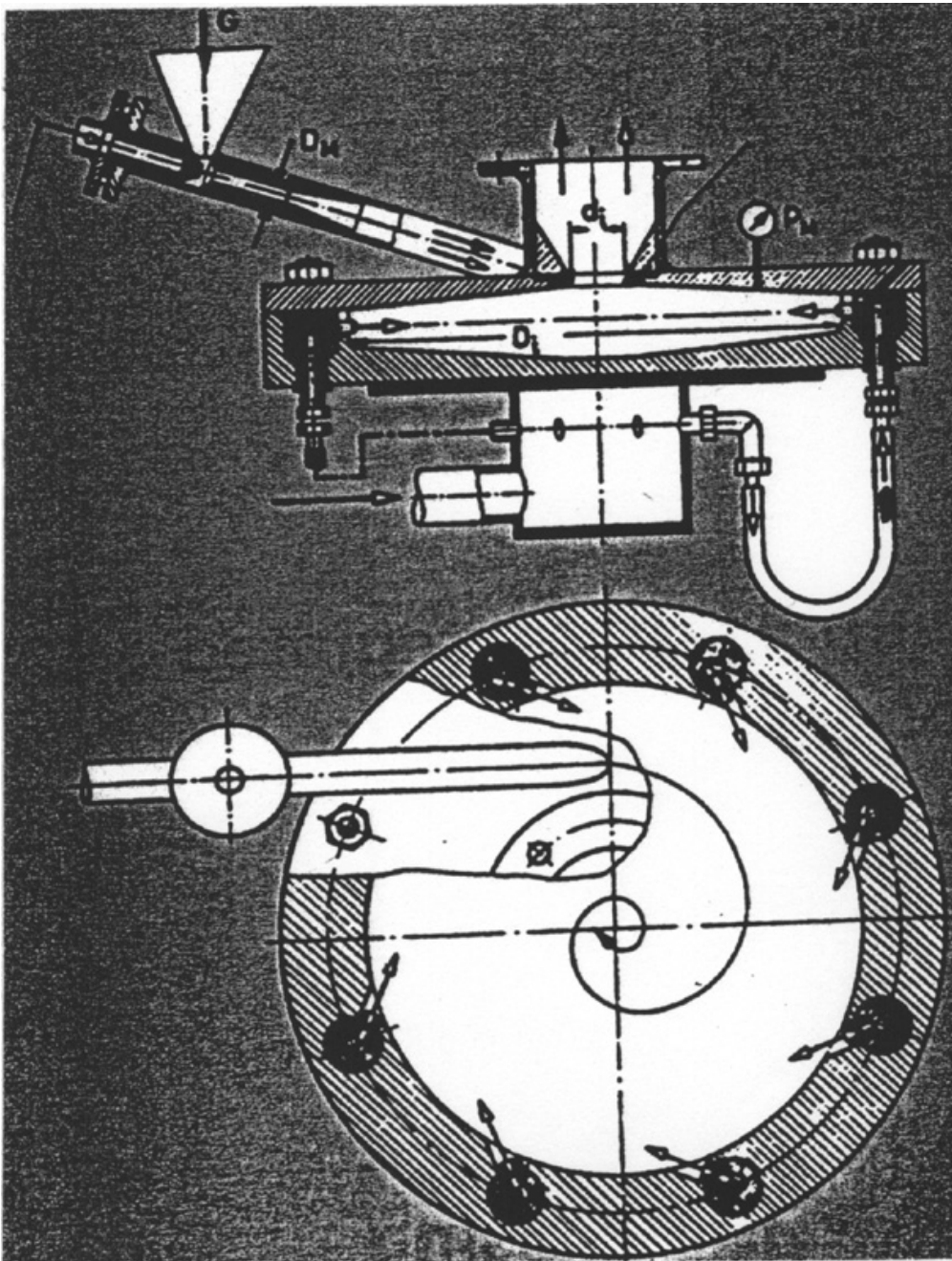


Figure 21

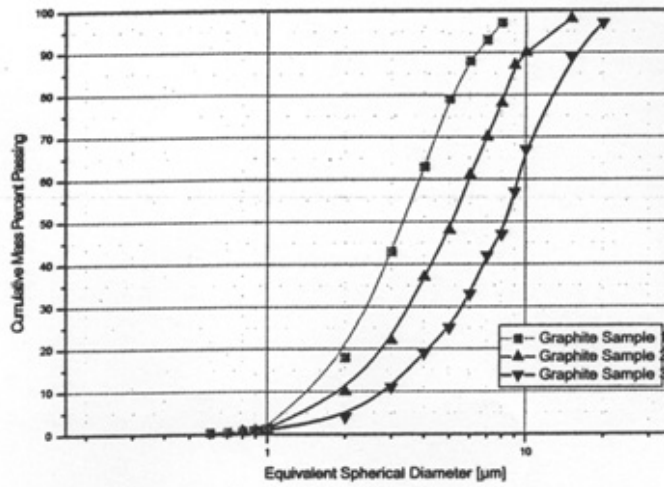
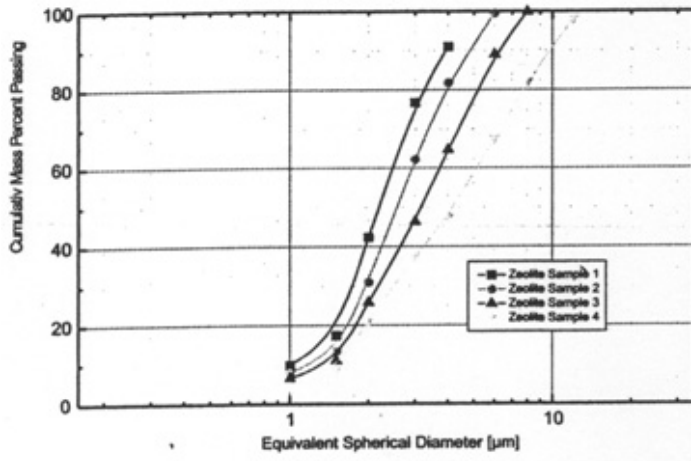
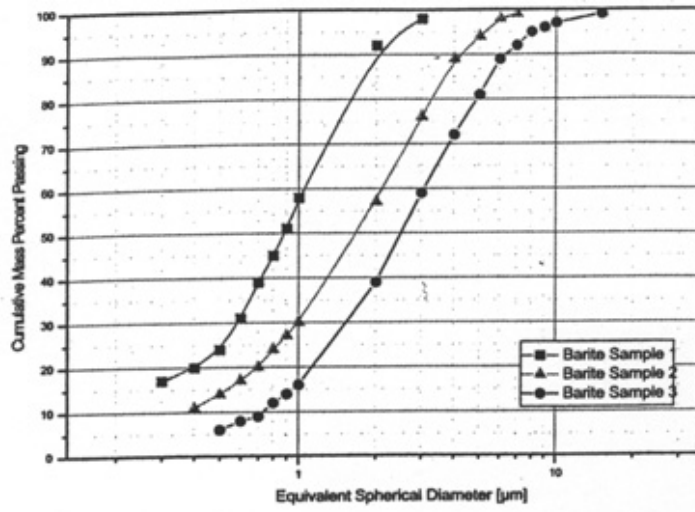


Figure 22

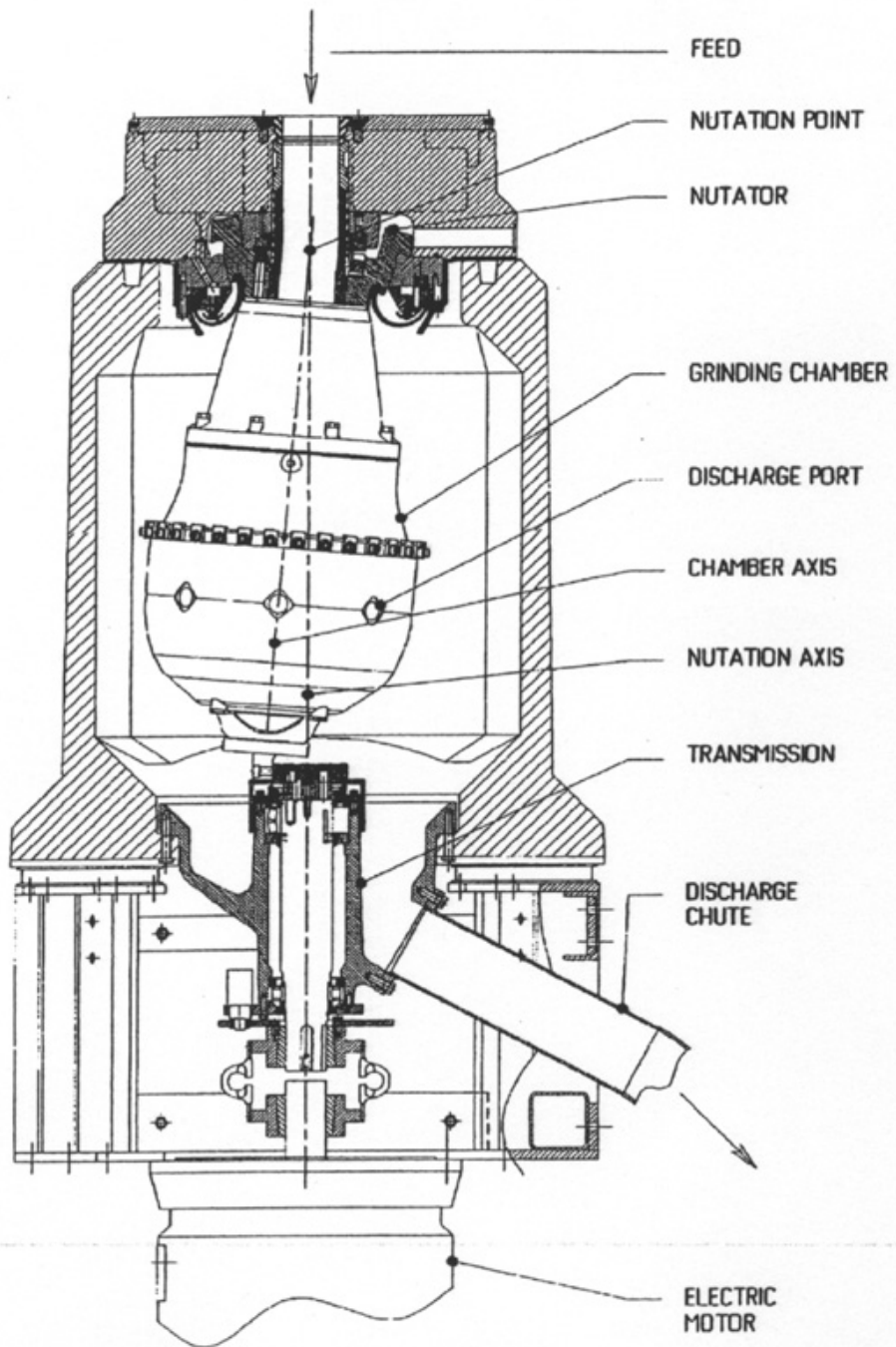


Figure 23

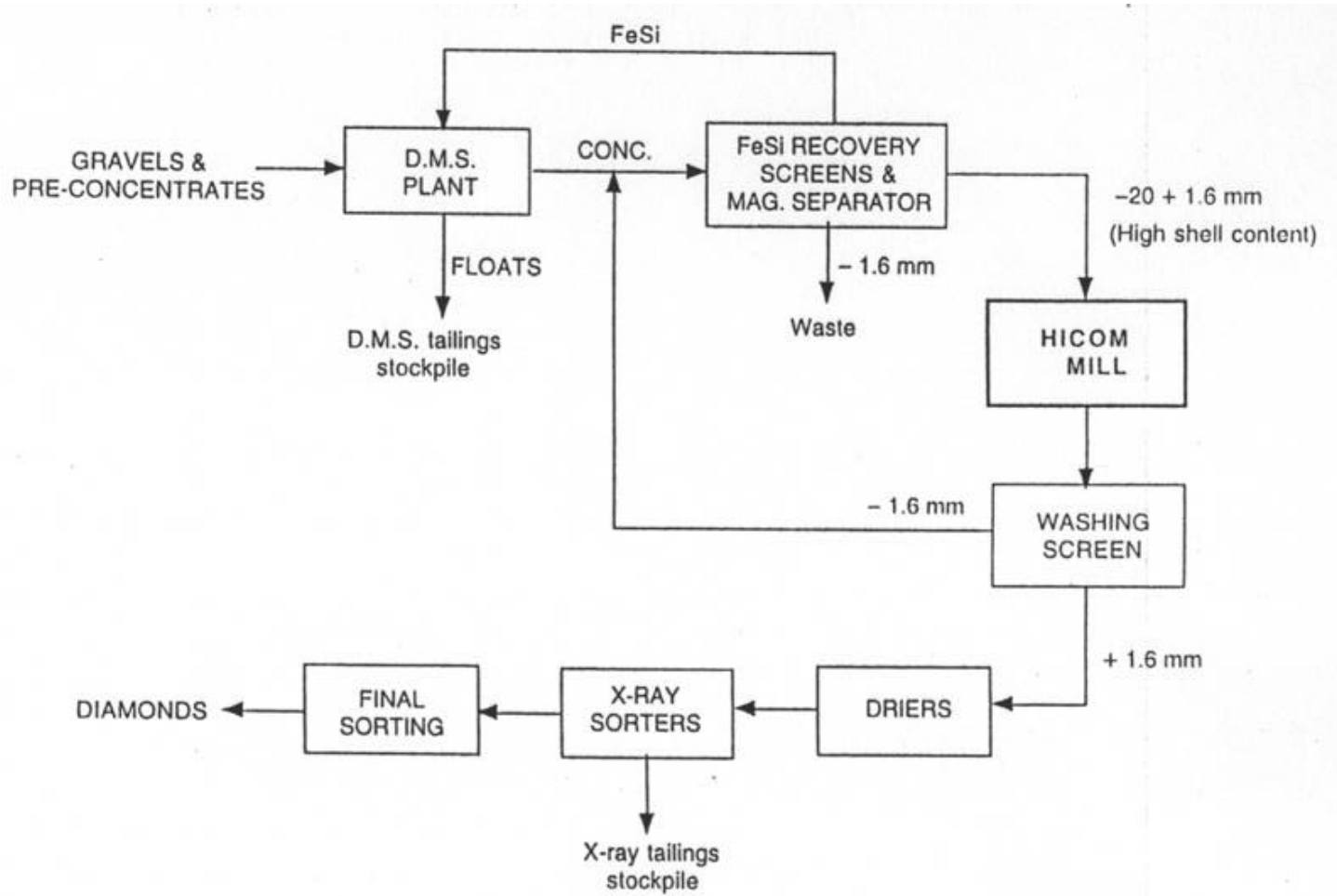


Figure 24

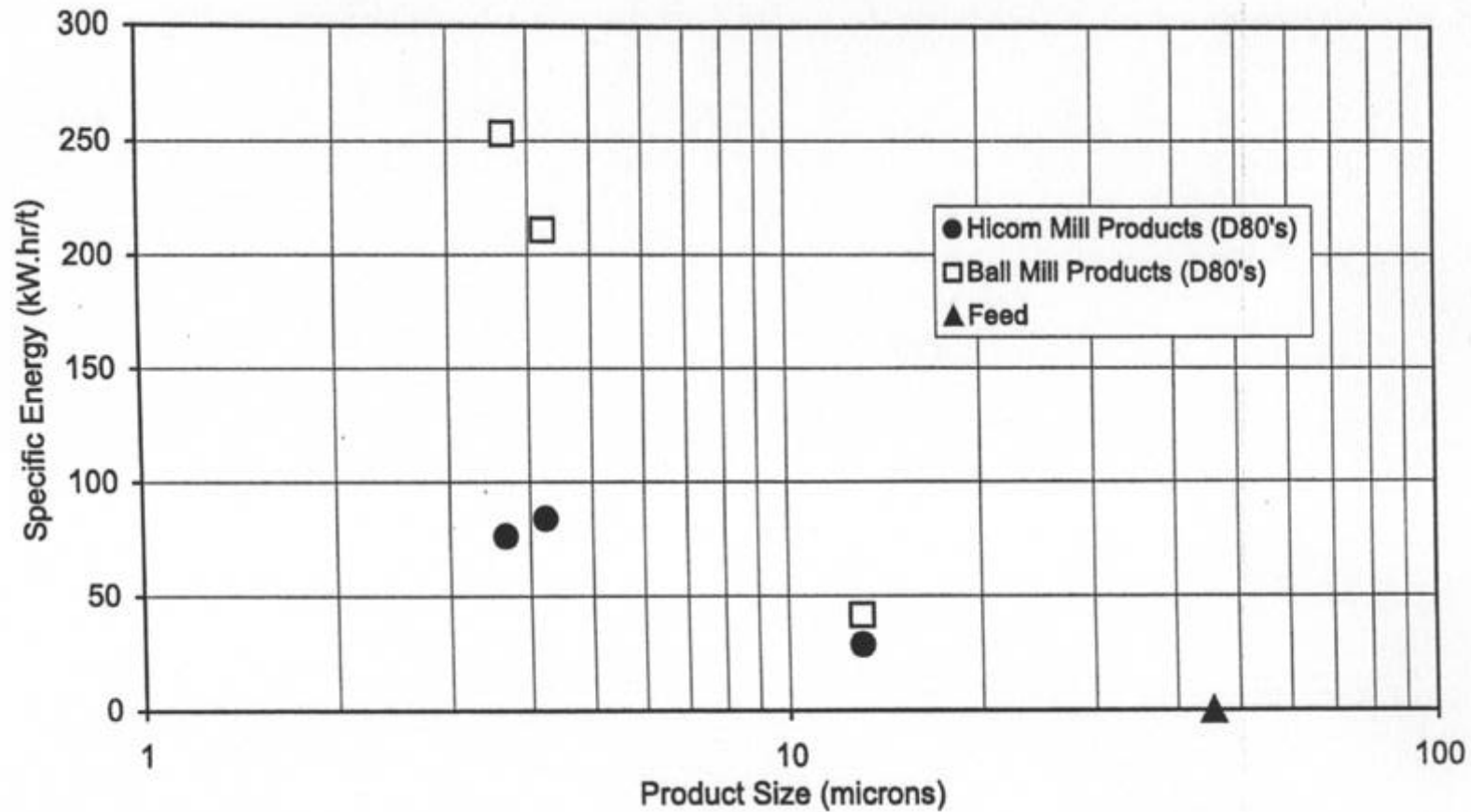


Figure 25

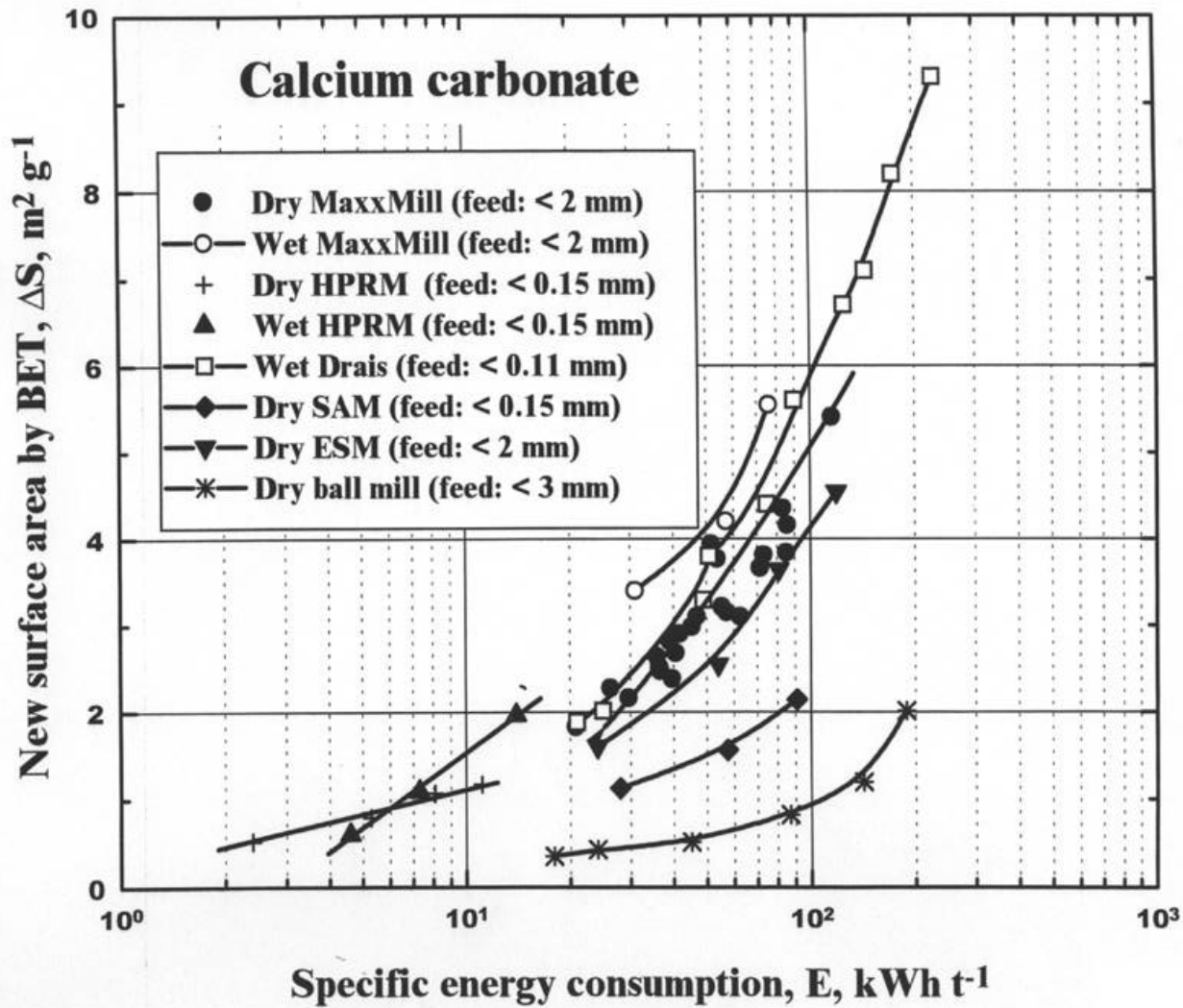


Figure 26

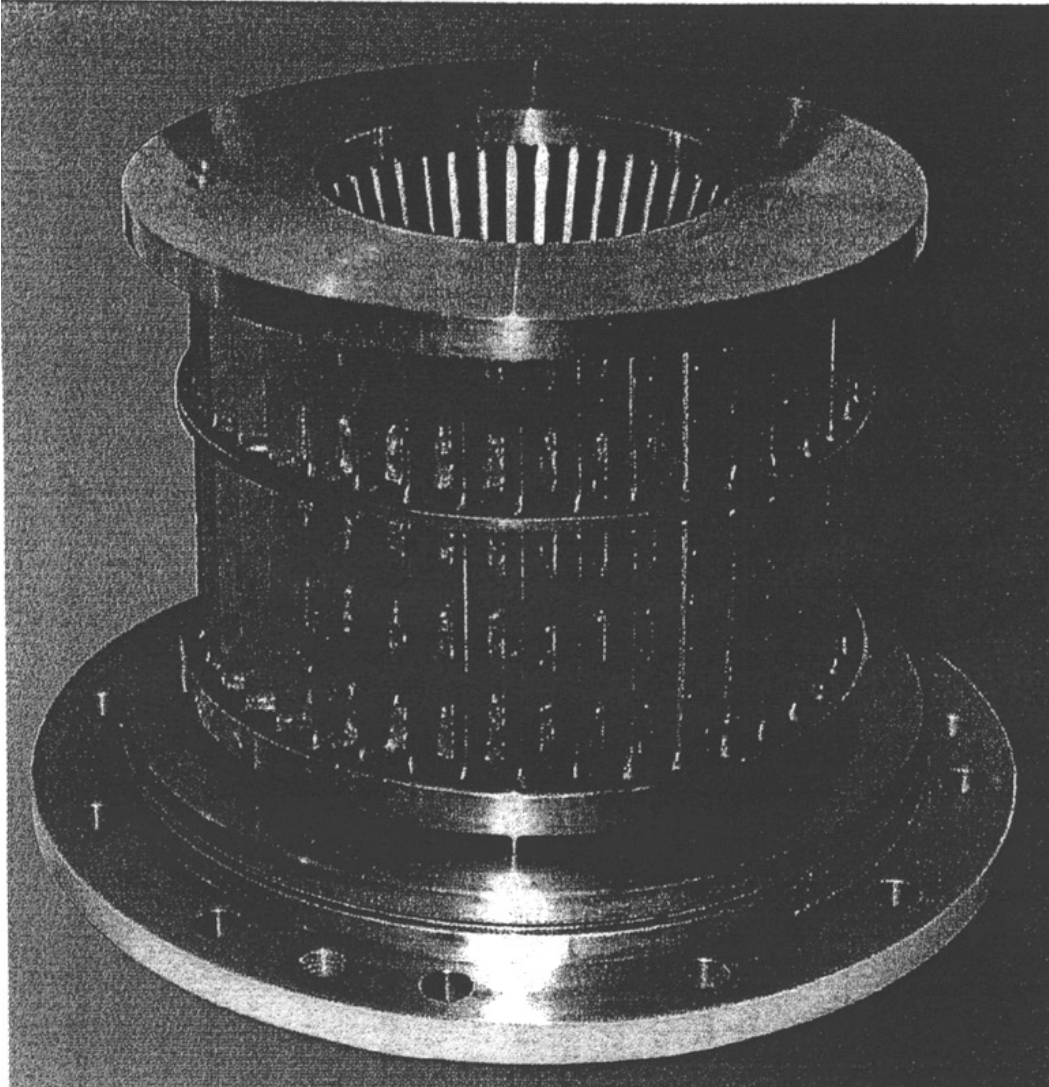


Figure 27

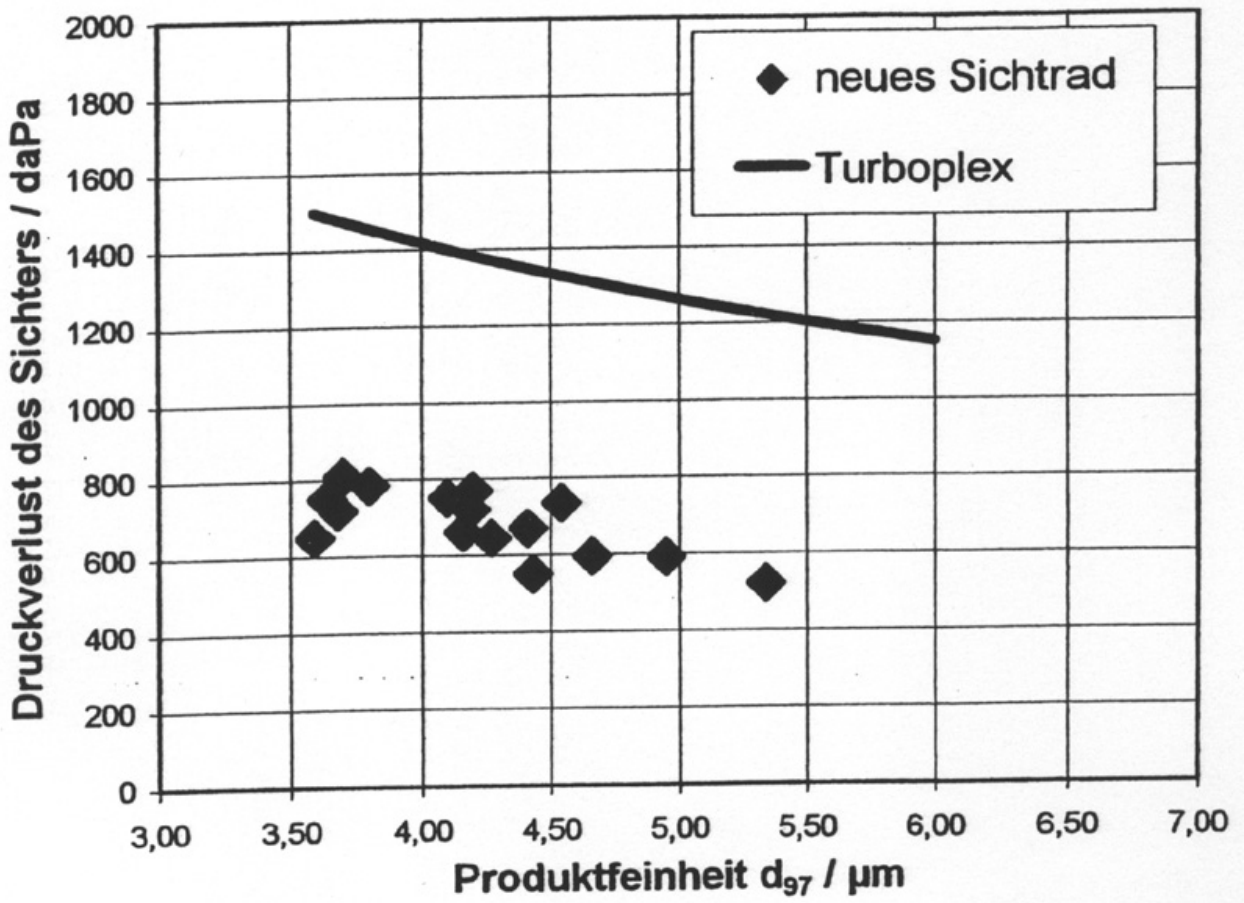


Figure 28

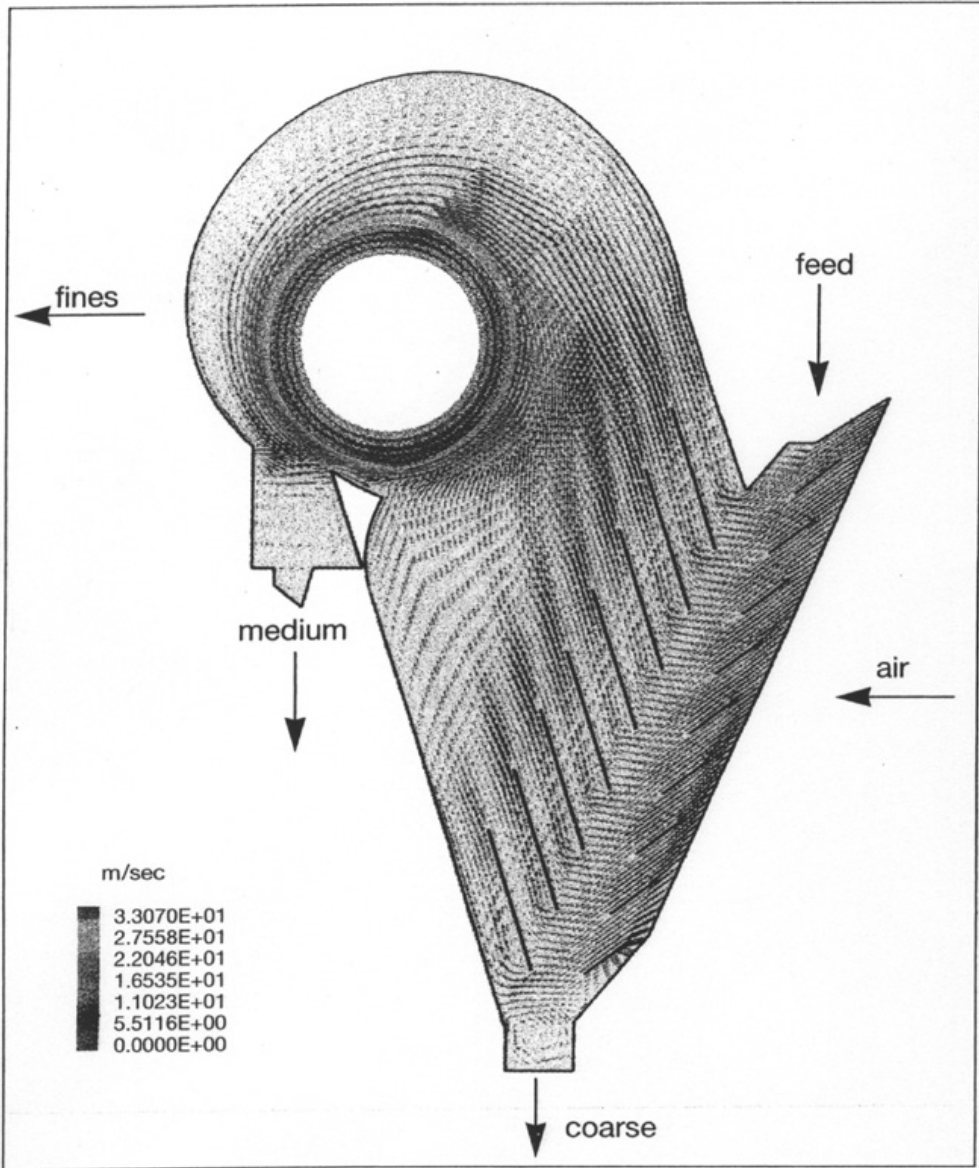


Figure 29

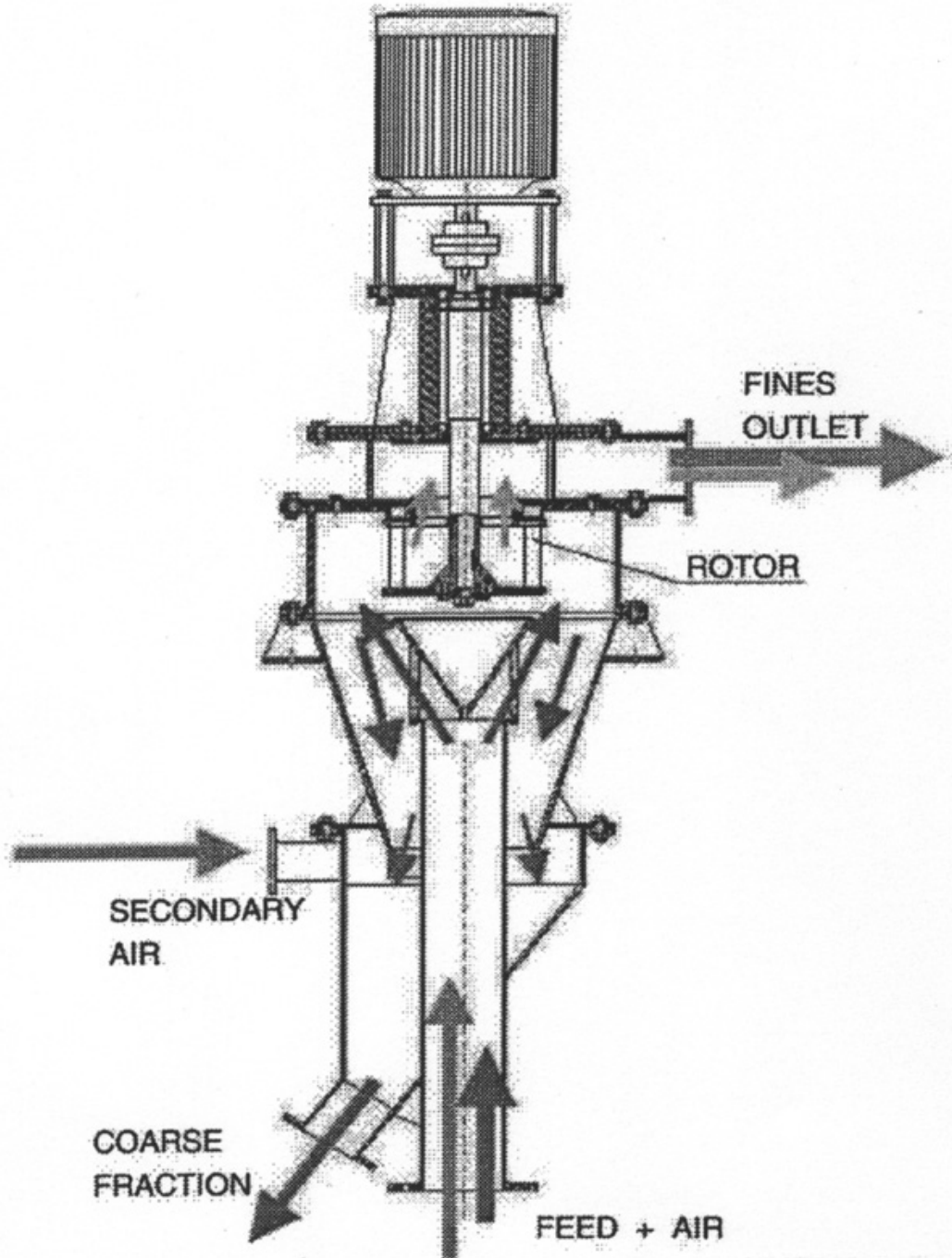


Figure 30

Inside Look at an Alfa Laval Nozzle Bowl Centrifuge

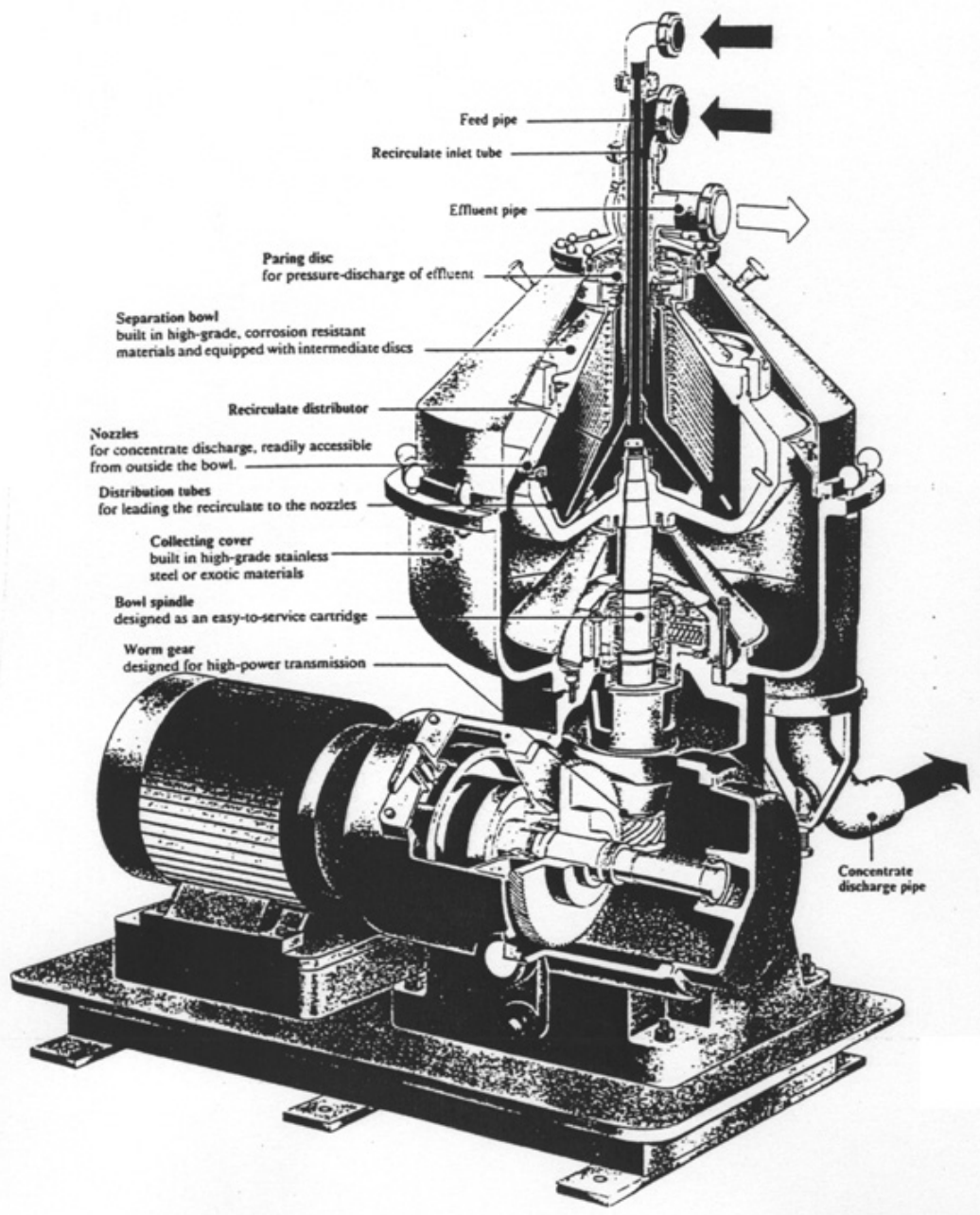


Figure 31

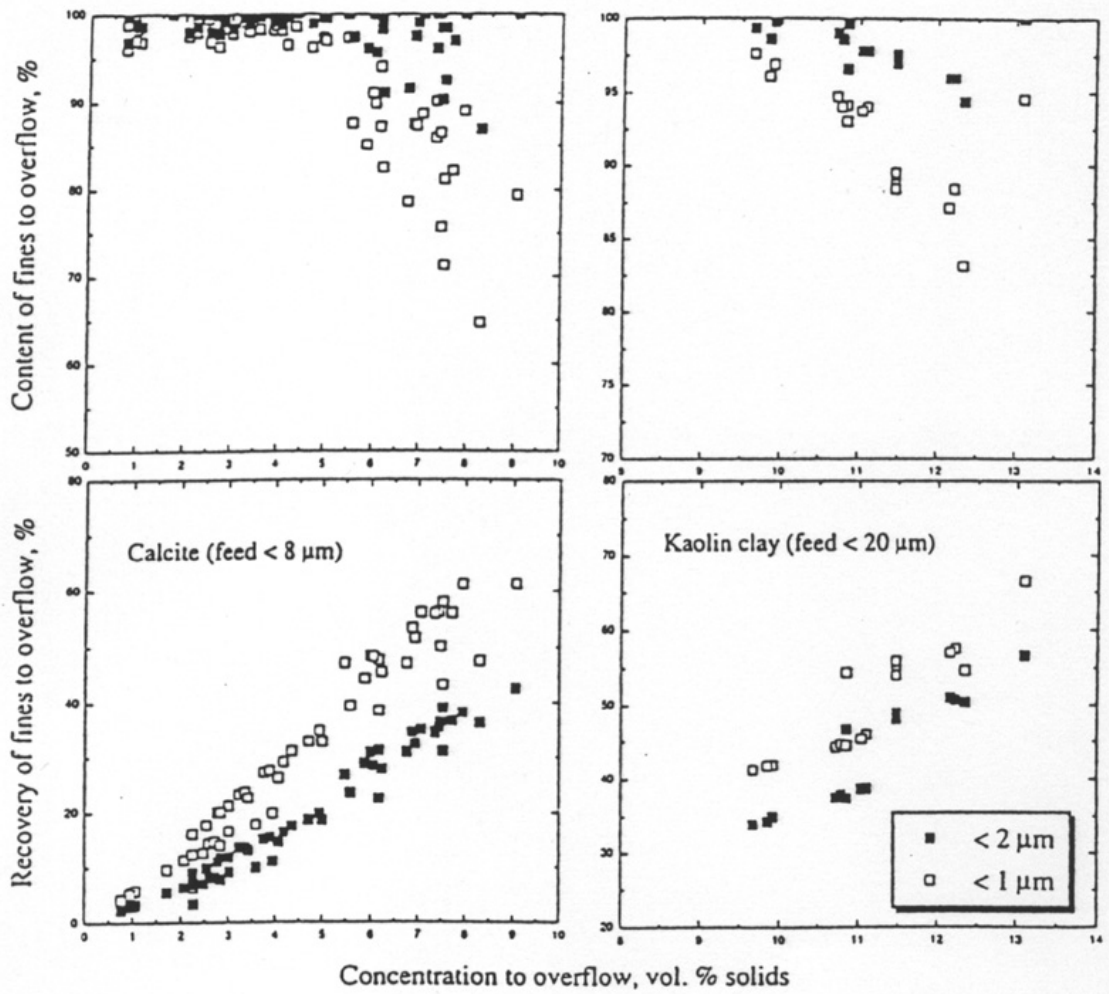


Figure 32

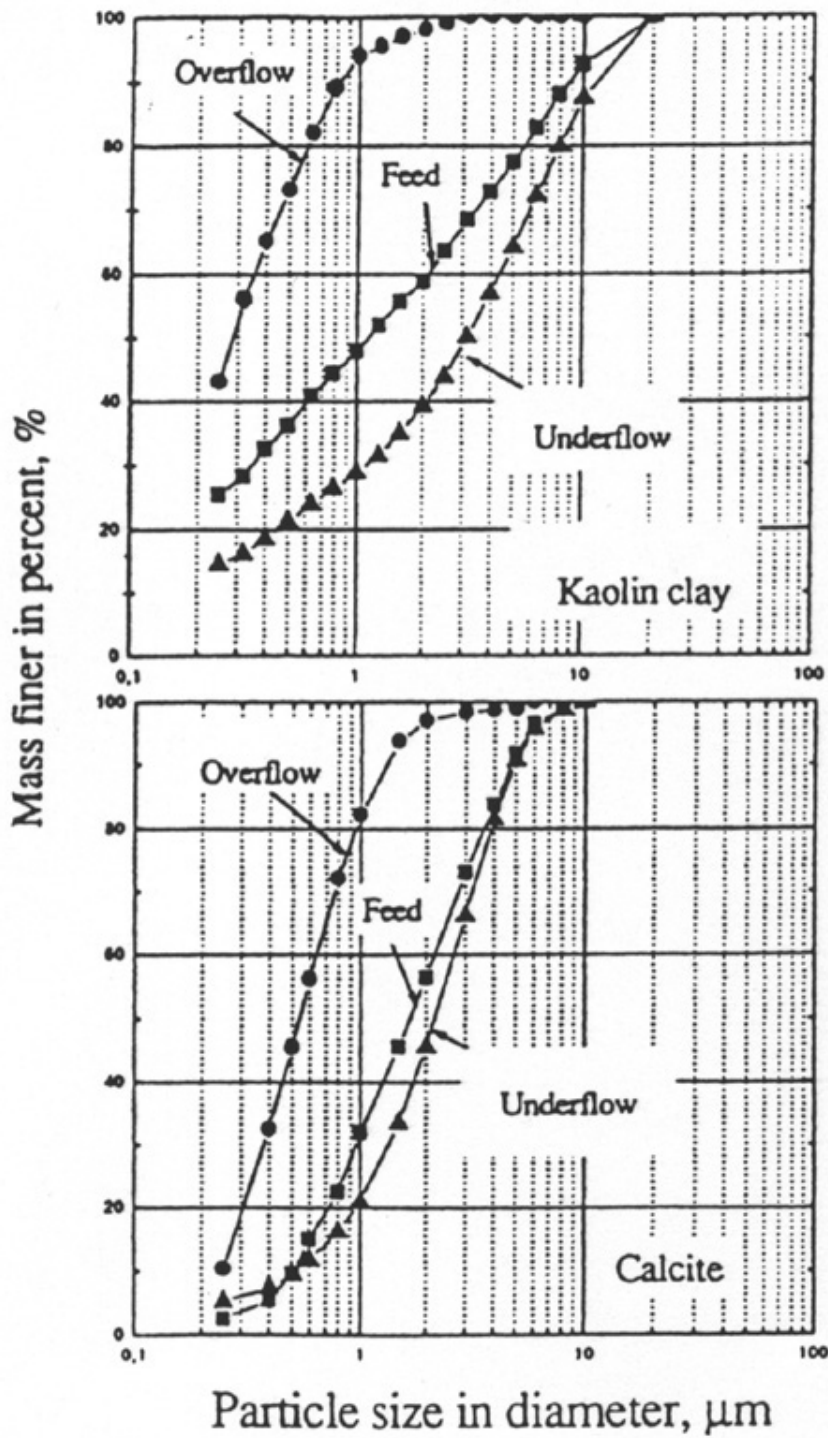


Figure 33

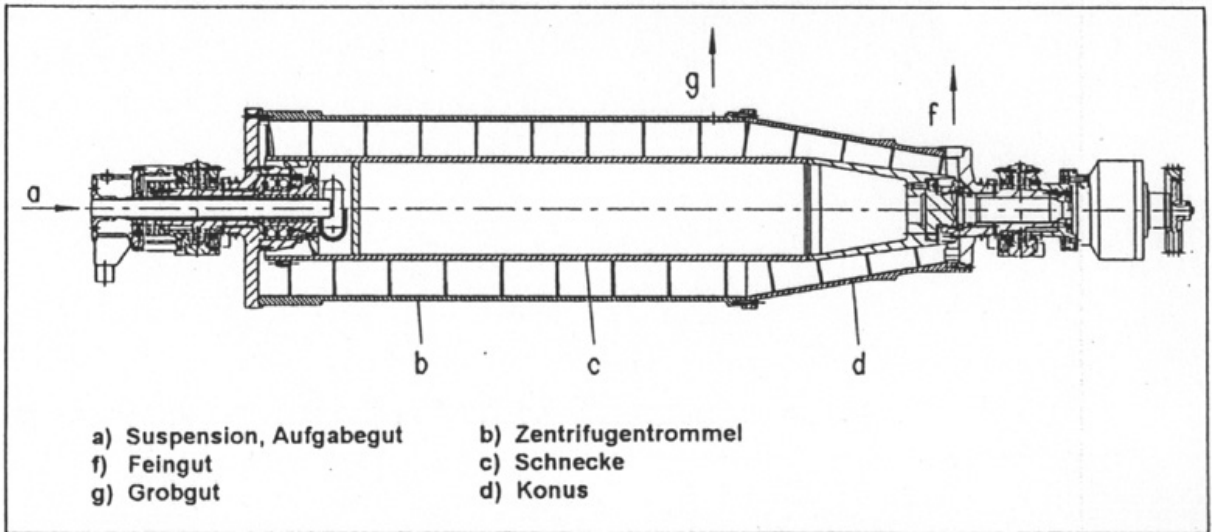
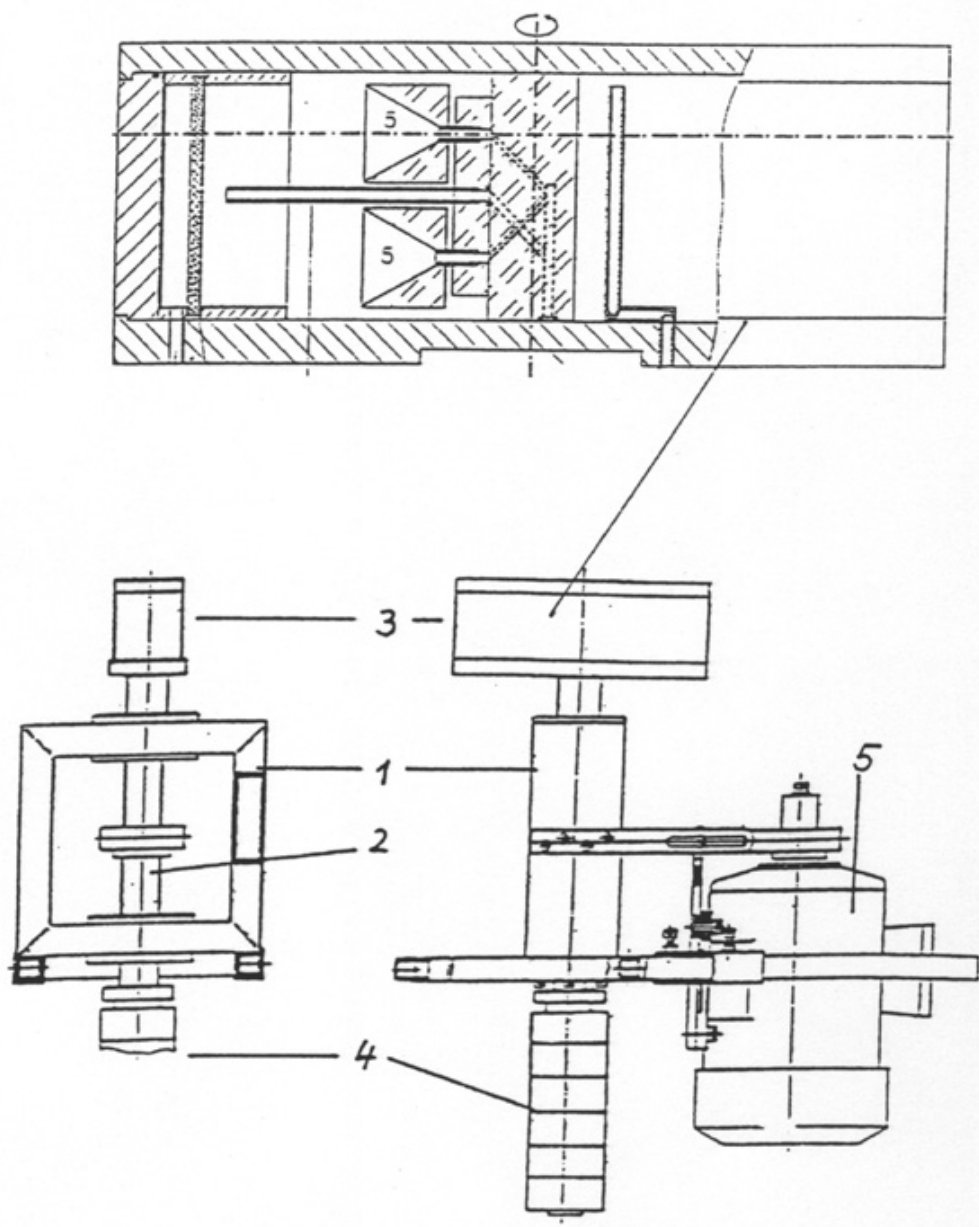


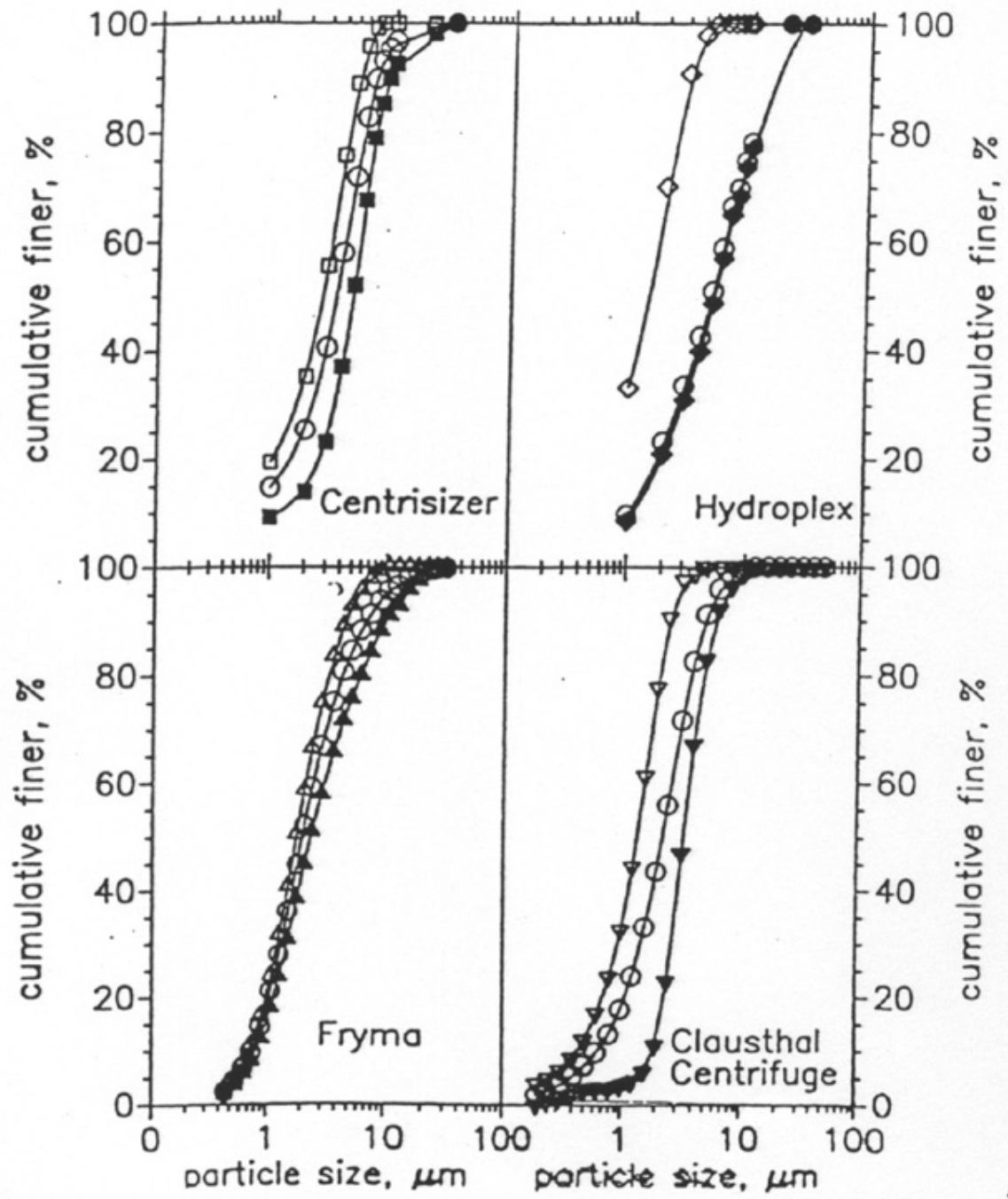
Figure 34



1 - frame; 2 - shaft; 3 - Ashlar-shaped rotor;
 4 - rotating joints; 5 - motor

Figure 35

Calcite finer 20 to 30 μm



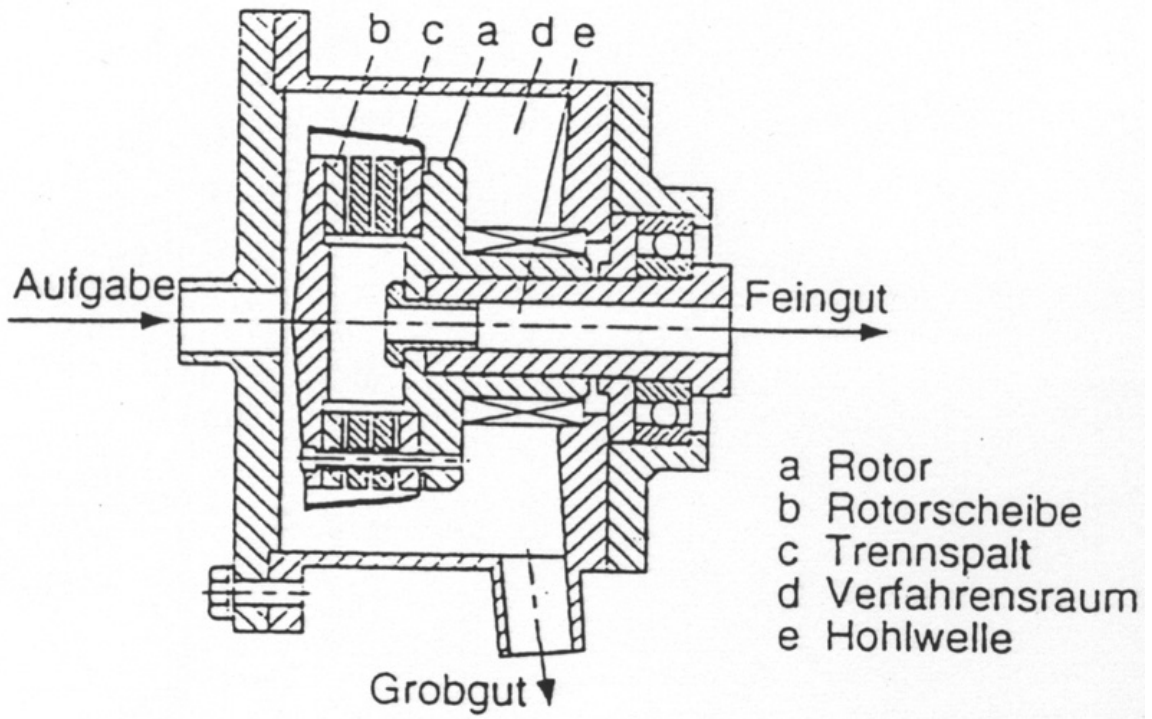


Figure 37

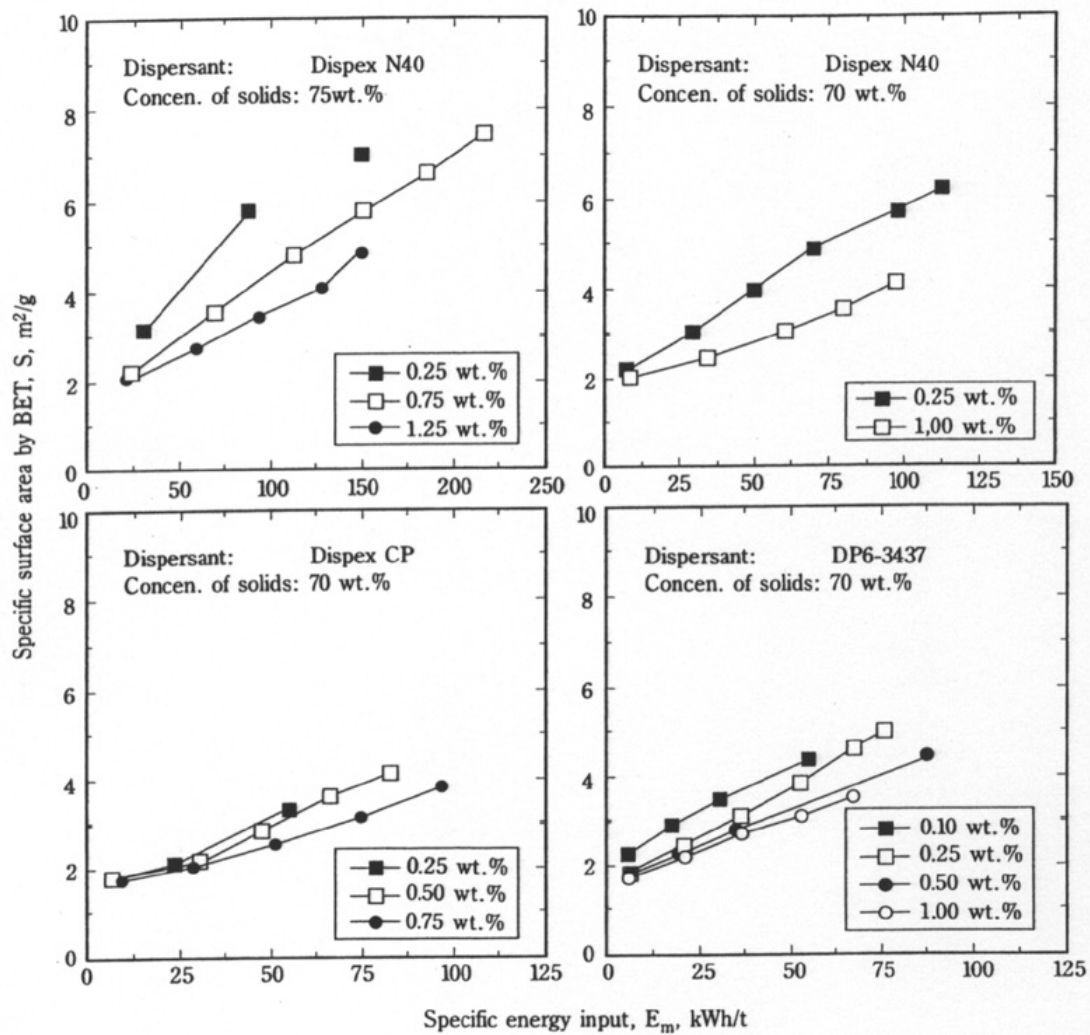


Figure 38

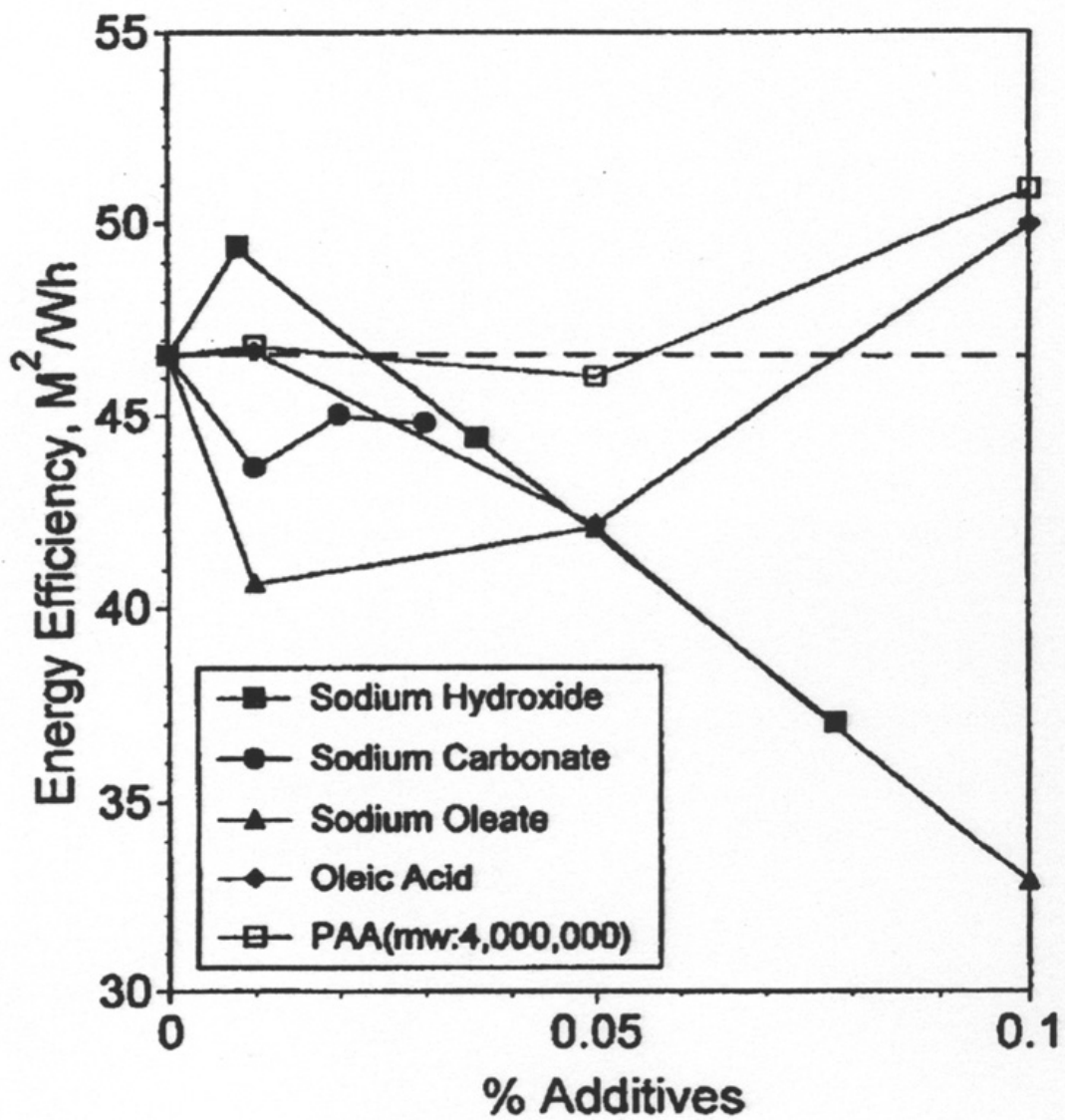


Figure 39

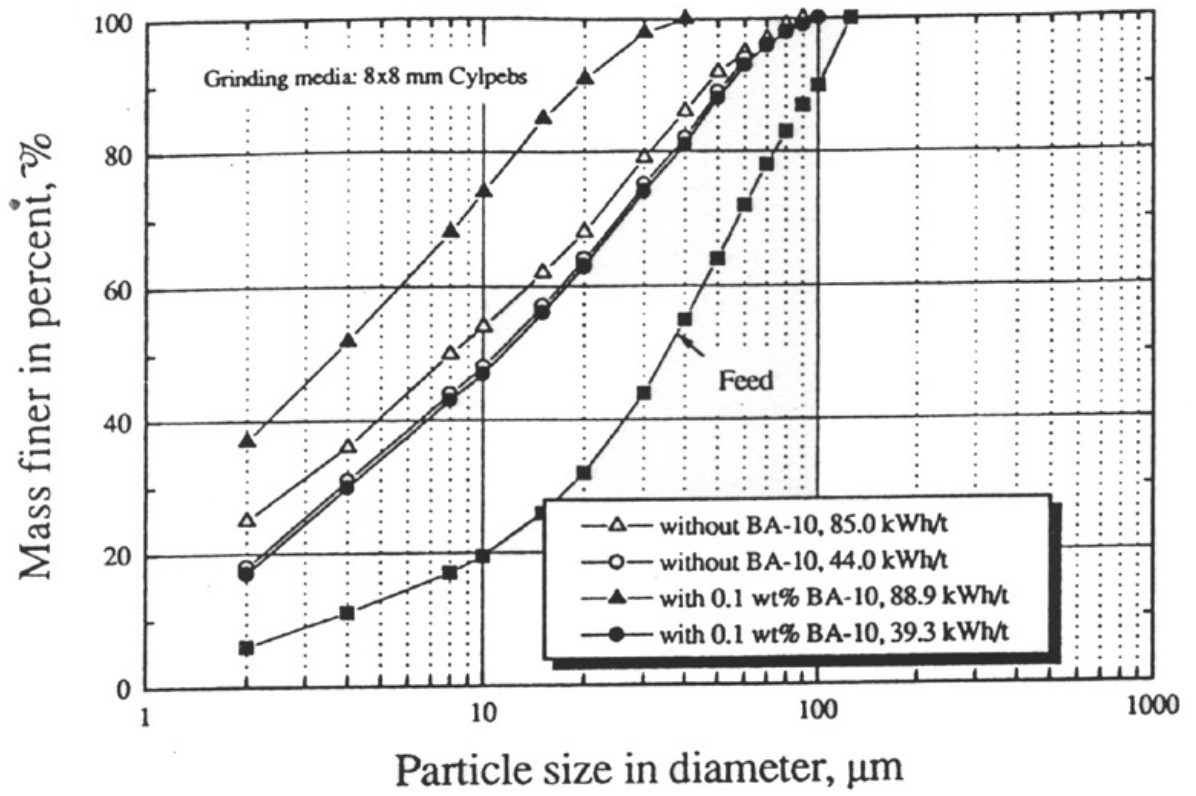


Figure 40

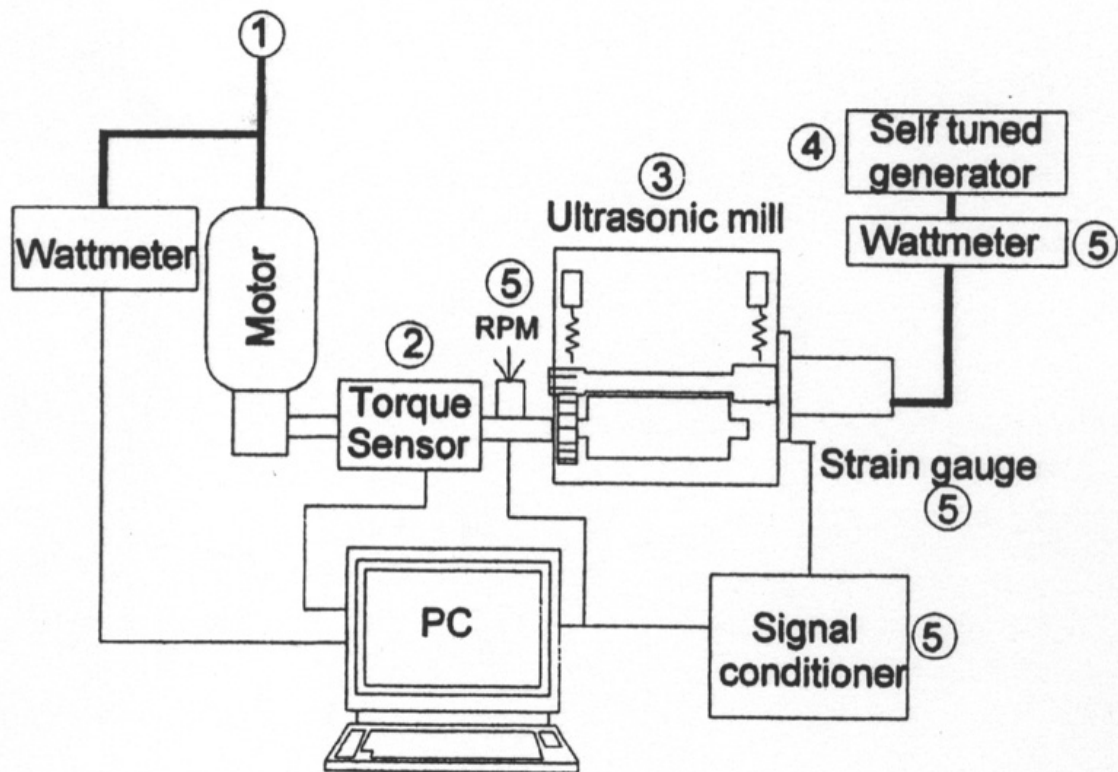


Figure 41

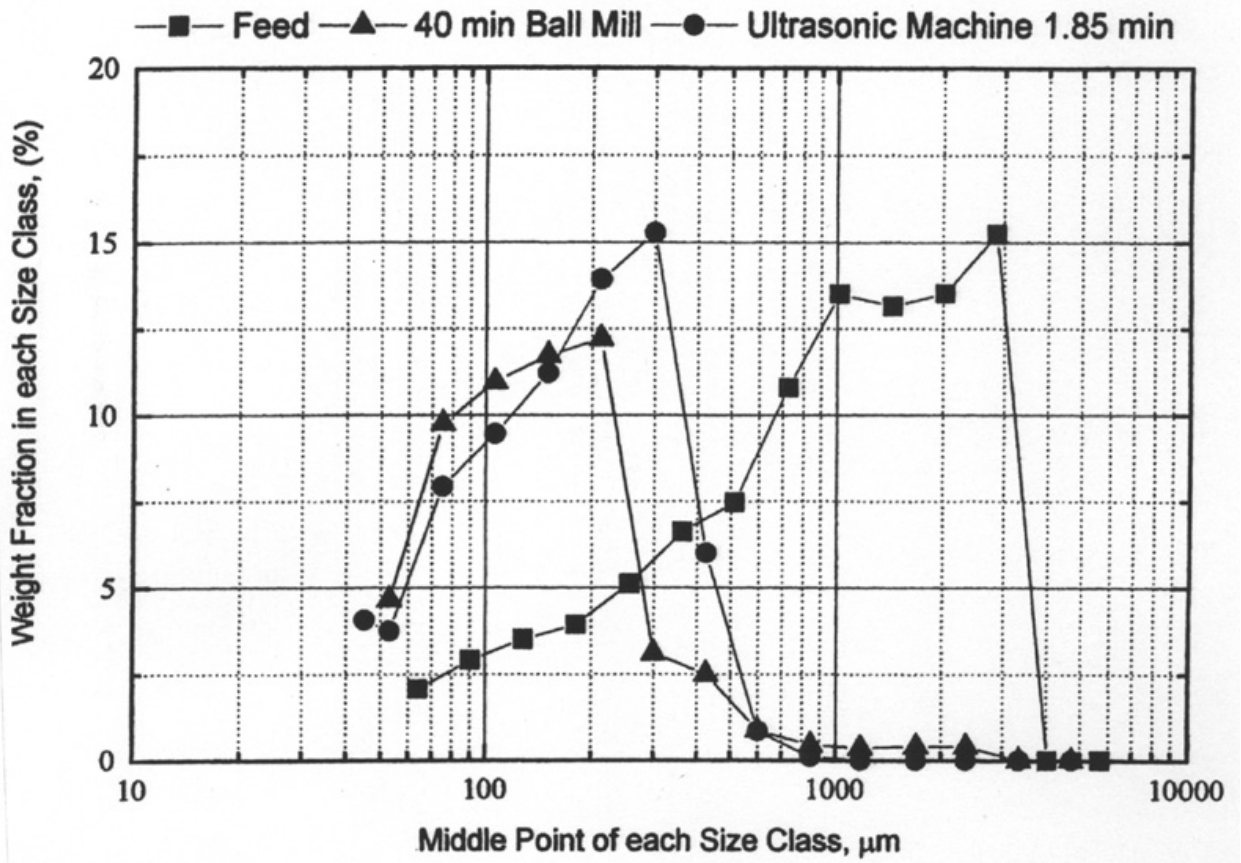


Figure 42

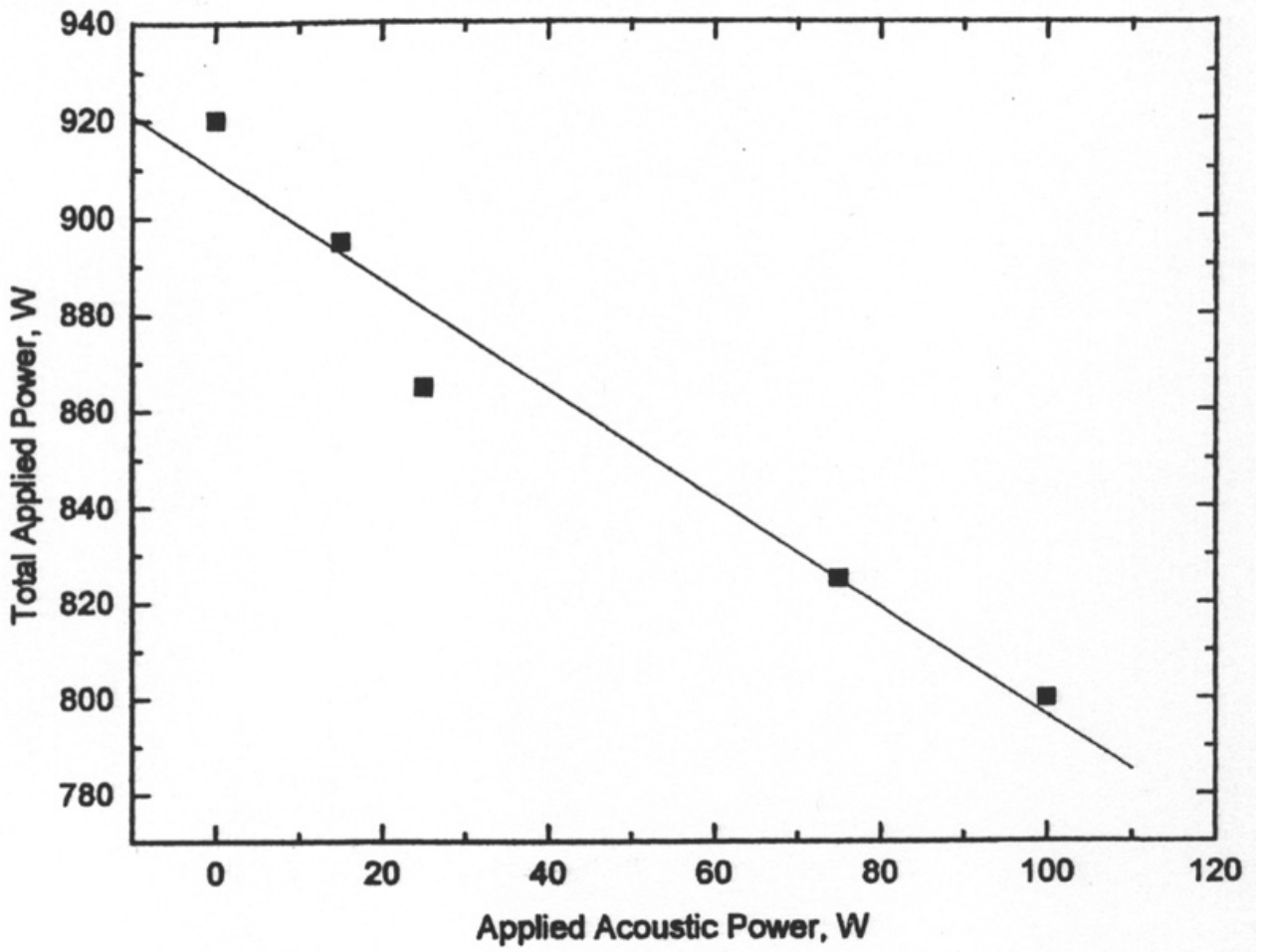


Figure 43

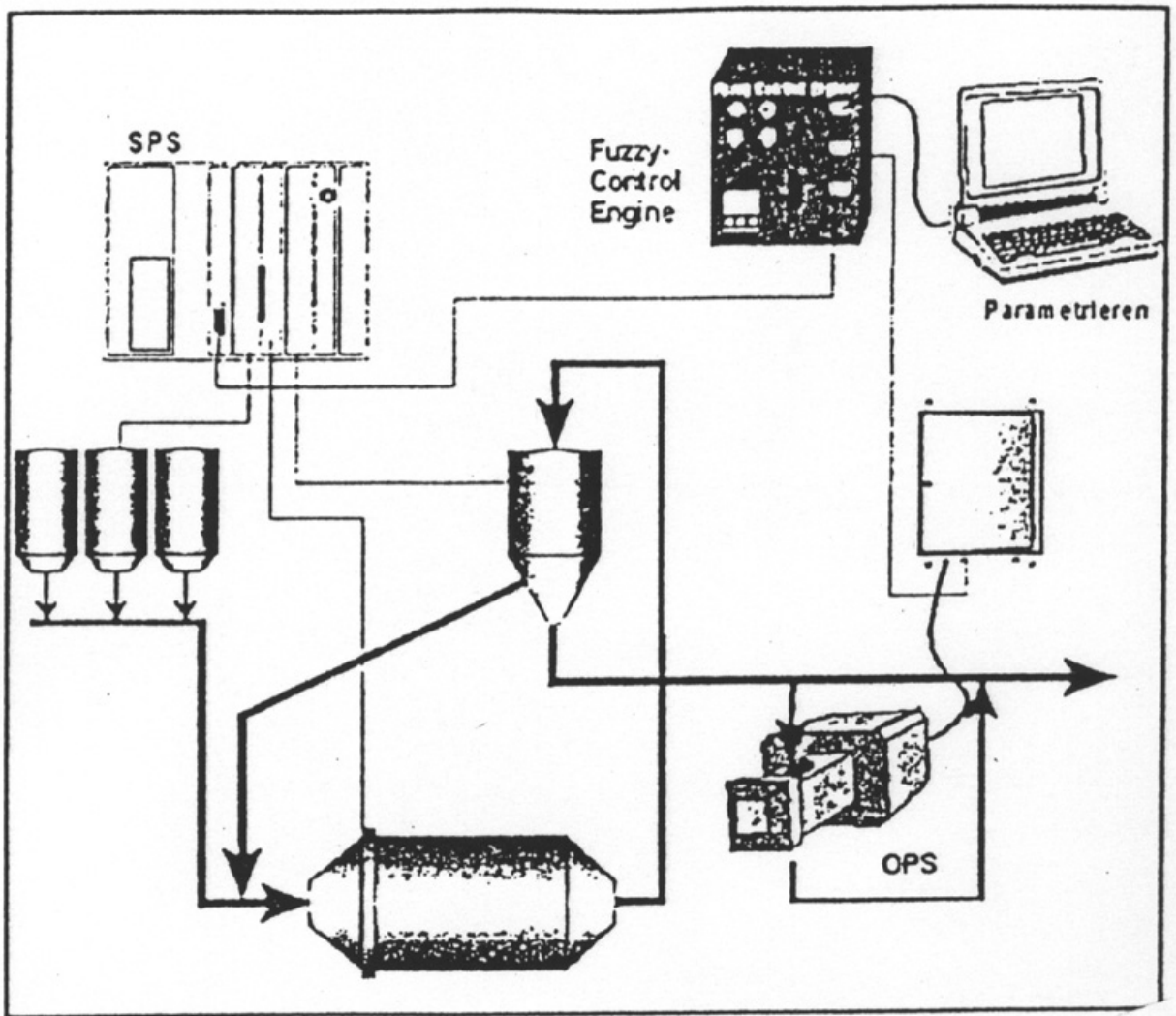


Figure 44

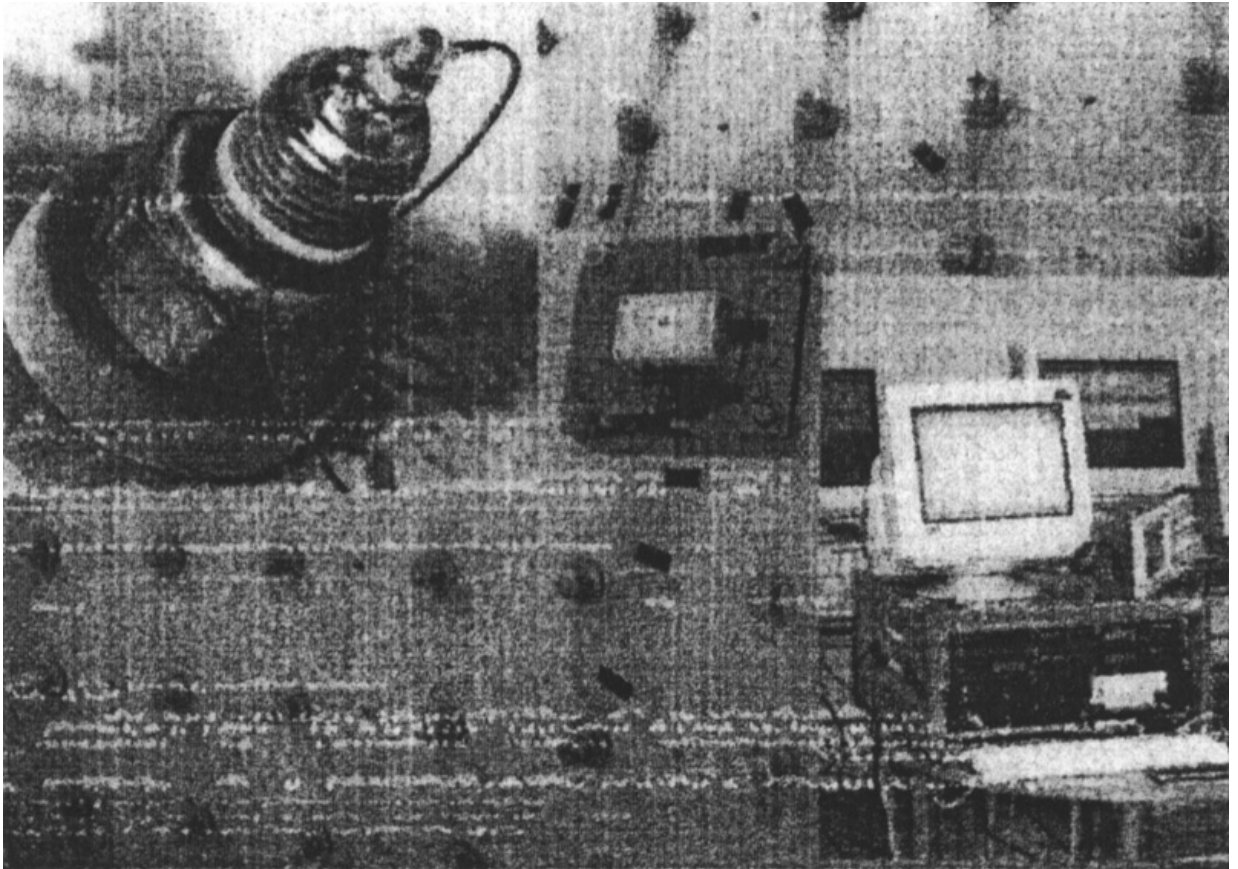


Figure 45

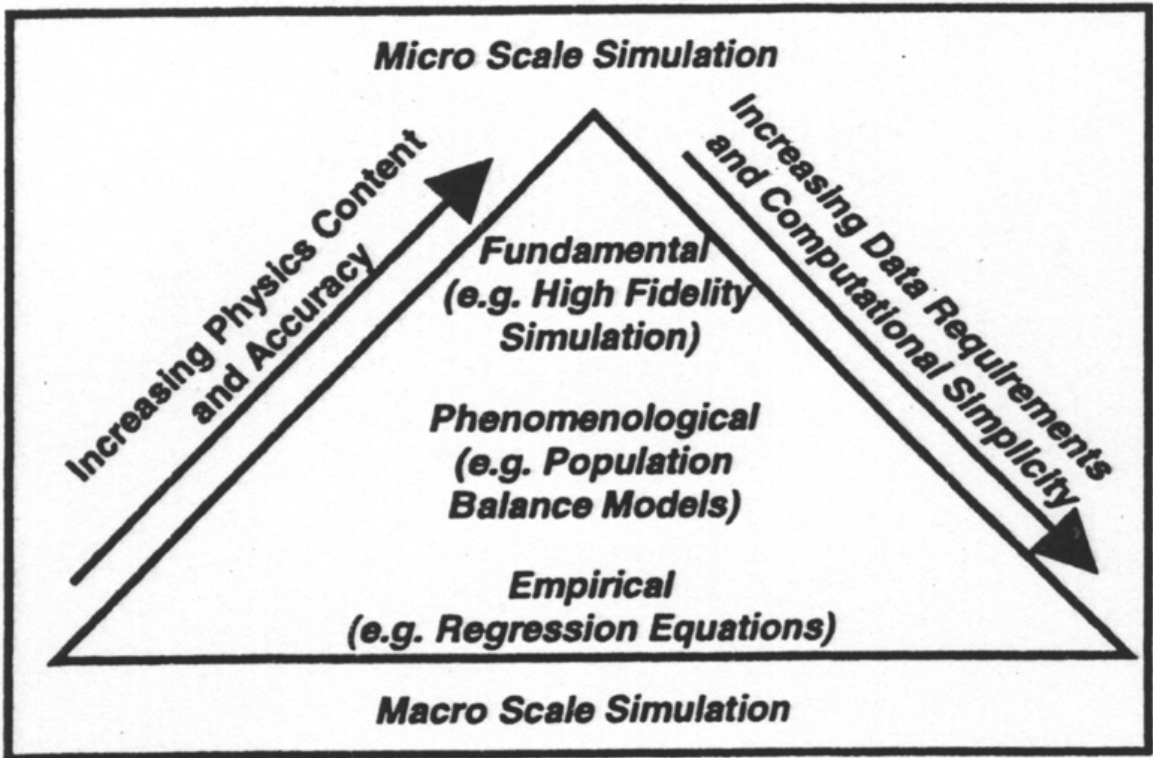


Figure 46

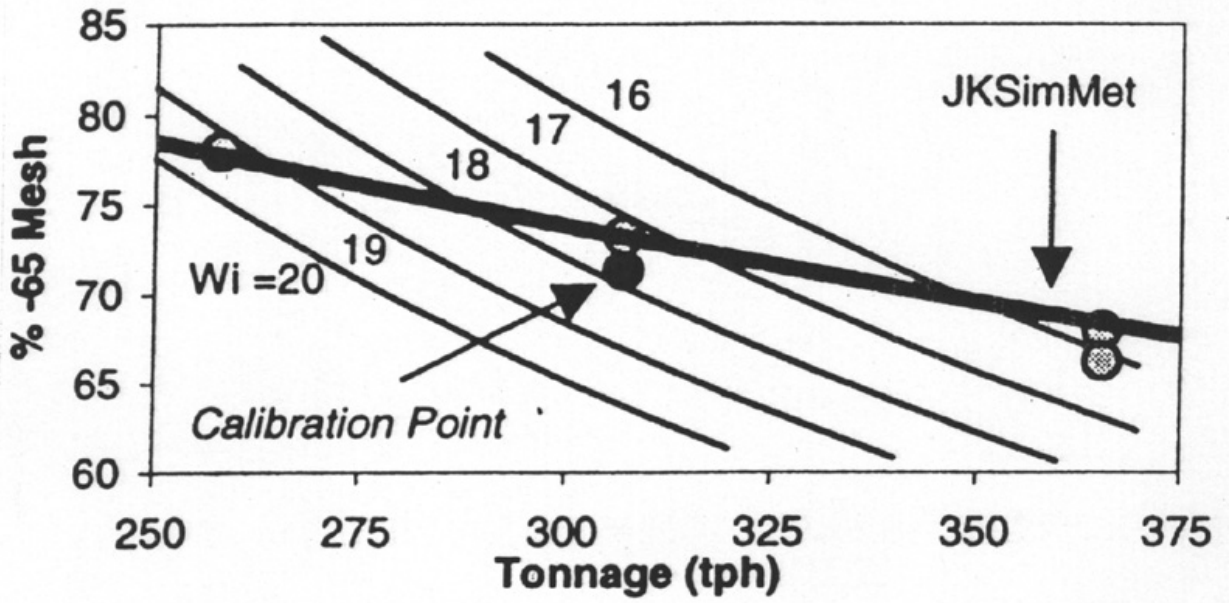


Figure 46

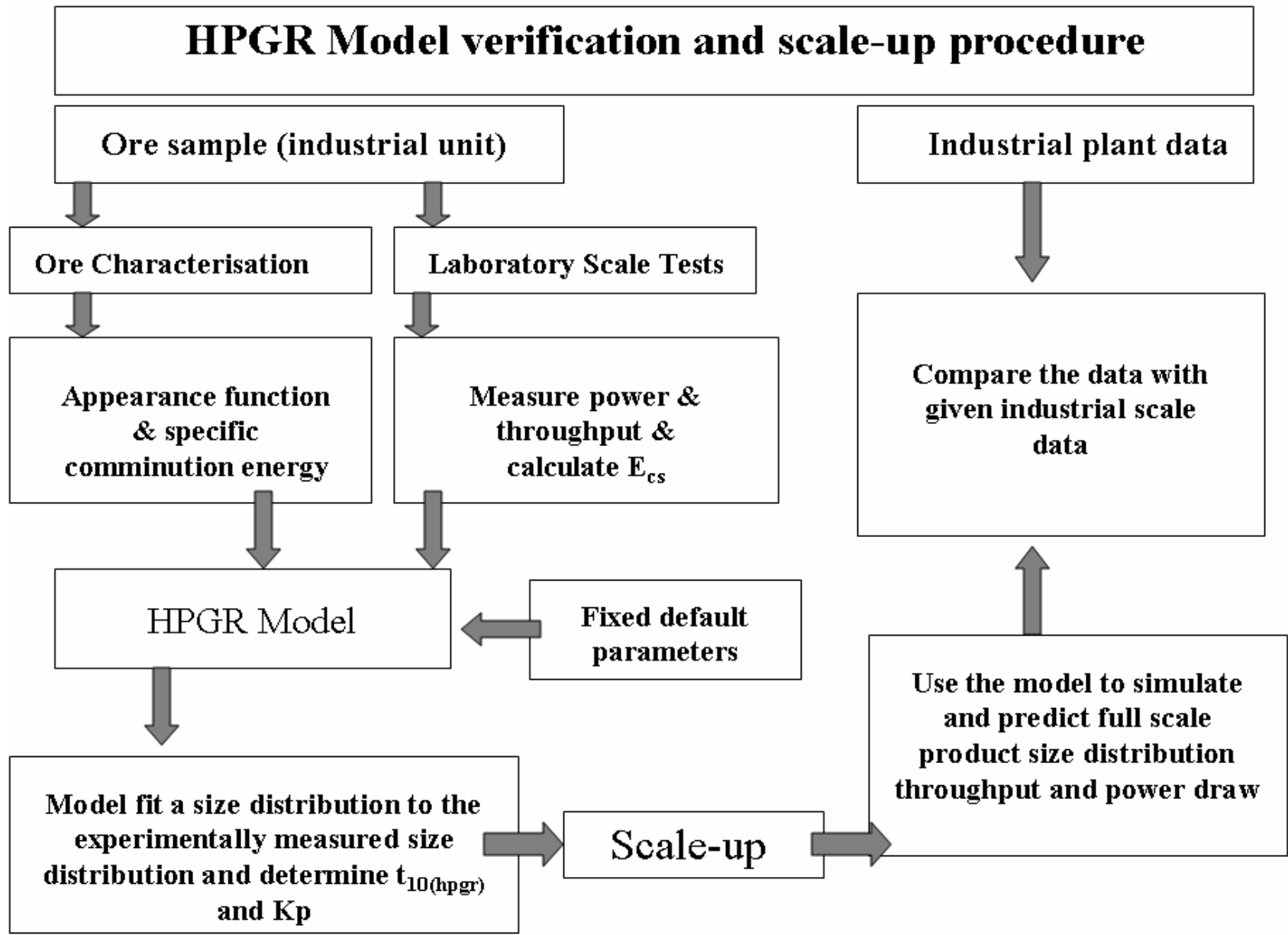
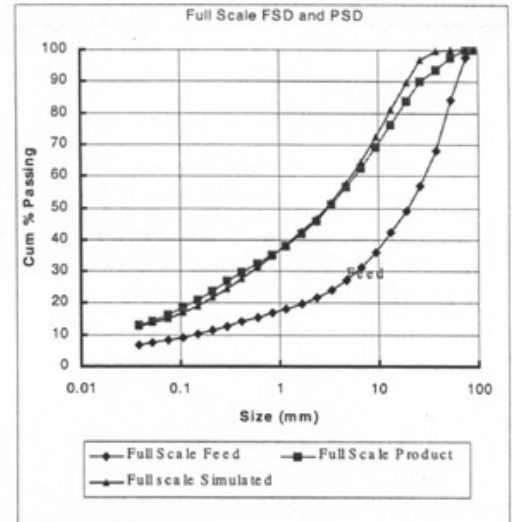
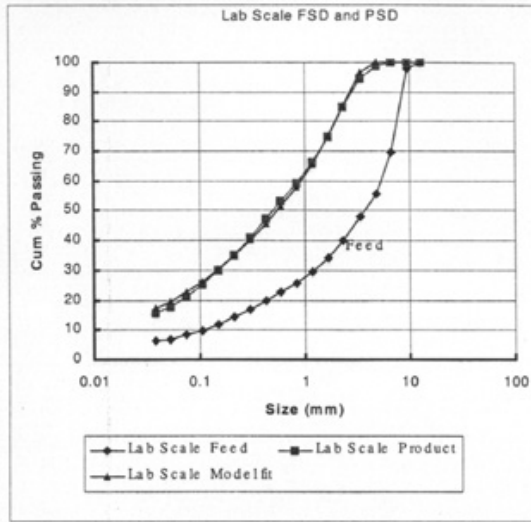


Figure 48

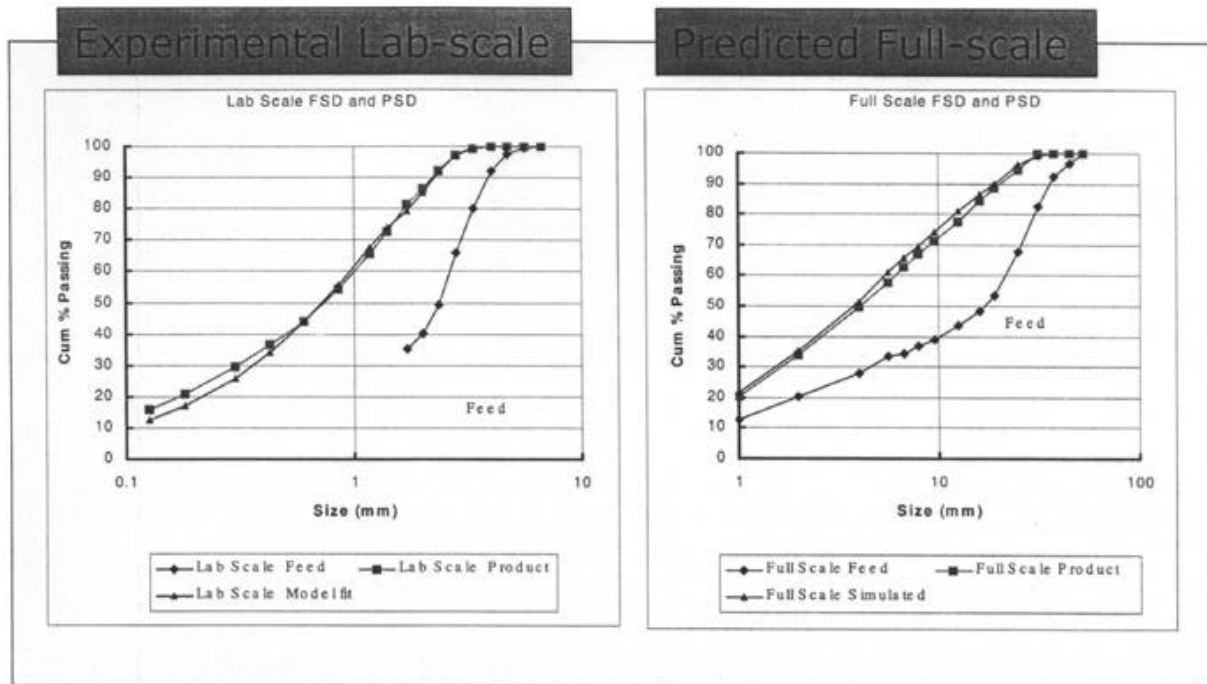
Experimental Lab-scale

Predicted Full-scale



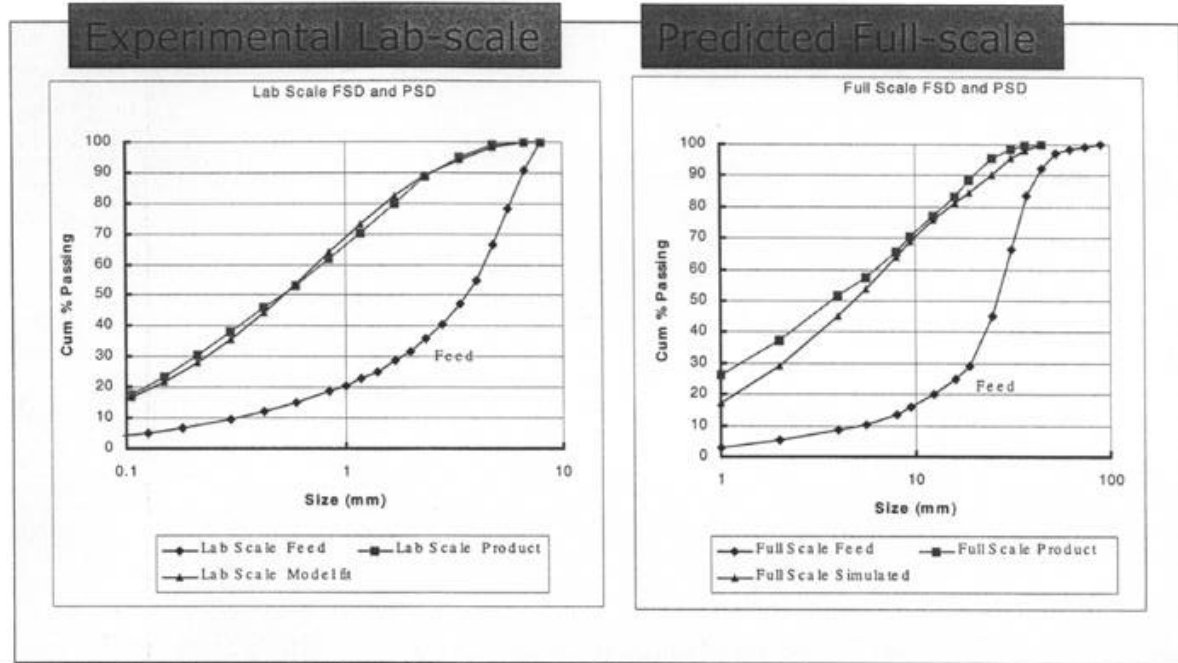
Data Source	Roll Surface	Roll Size (m)	kWh/t (full-scale)	kWh/t (lab-scale)
Rio Tinto(historical)	Smooth	2.2	1.8-2.5	1.8-2.5
De Beers	Smooth	2.8	4.0-4.5	4.0-4.5
De Beers	Studded	2.8	2.5-3.0	3.5-3.9
BHP Billiton	Studded	1.7	1.0-1.2	2.0-3.0

Figure 49



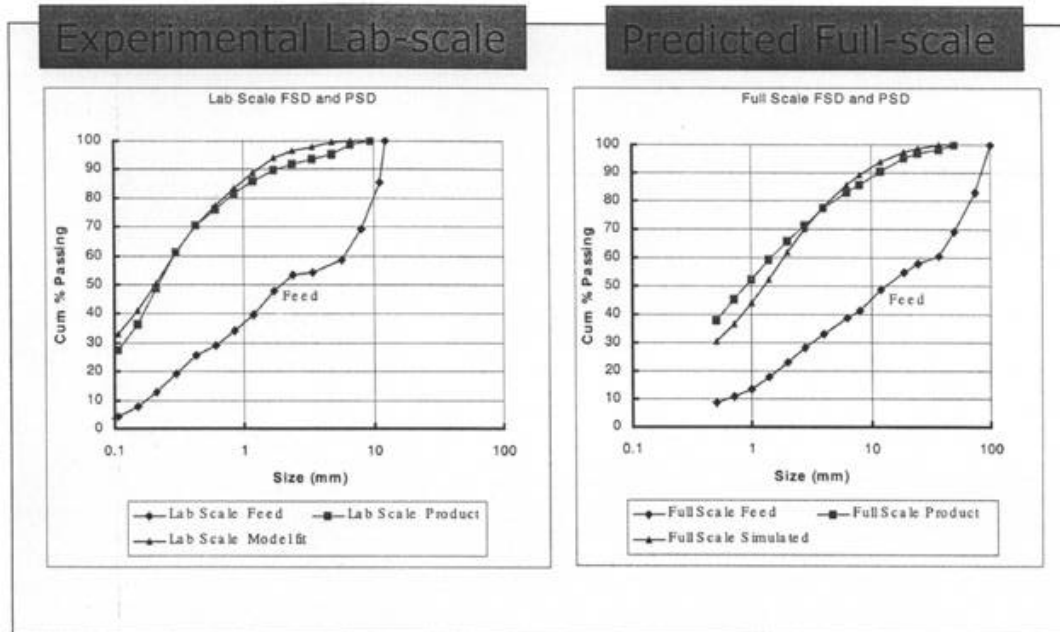
Data Source	Roll Surface	Roll Size (m)	kWh/t (full-scale)	kWh/t (lab-scale)
Rio Tinto (historical)	Smooth	2.2	1.8-2.5	1.8-2.5
De Beers	Smooth	2.8	4.0-4.5	4.0-4.5
De Beers	Studded	2.8	2.5-3.0	3.5-3.9
BHP Billiton	Studded	1.7	1.0-1.2	2.0-3.0

Figure 50



Data Source	Roll Surface	Roll Size (m)	kWh/t (full-scale)	kWh/t (lab-scale)
Rio Tinto (historical)	Smooth	2.2	1.8-2.5	1.8-2.5
De Beers	Smooth	2.8	4.0-4.5	4.0-4.5
De Beers	Studded	2.8	2.5-3.0	3.5-3.9
BHP Billiton	Studded	1.7	1.0-1.2	2.0-3.0

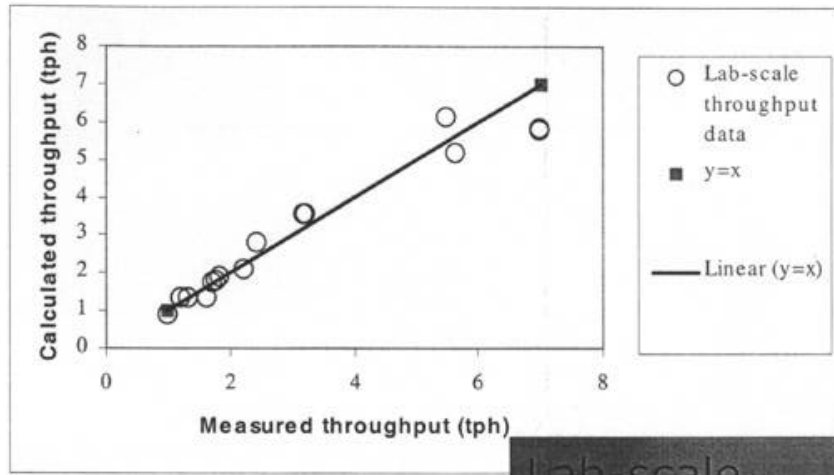
Figure 51



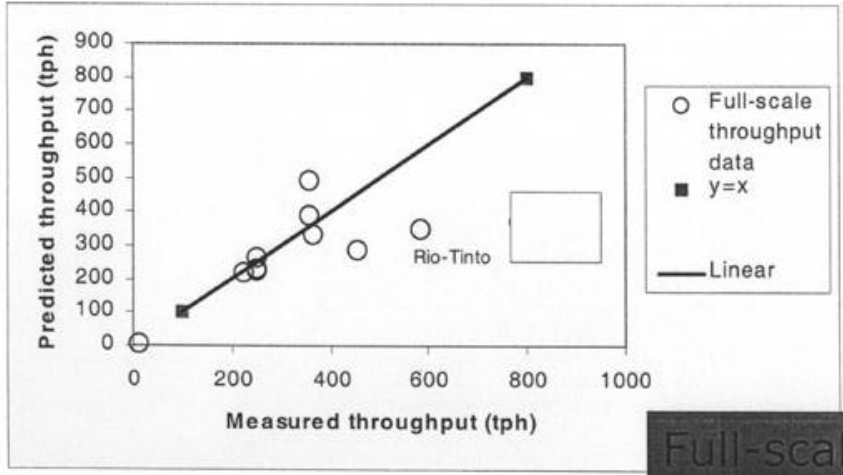
Data Source	Roll Surface	Roll Size (m)	kWh/t (full-scale)	kWh/t (lab-scale)
Rio Tinto (historical)	Smooth	2.2	1.8-2.5	1.8-2.5
De Beers	Smooth	2.8	4.0-4.5	4.0-4.5
De Beers	Studded	2.8	2.5-3.0	3.5-3.9
BHP Billiton	Studded	1.7	1.0-1.2	2.0-3.0

Figure 52

Throughput

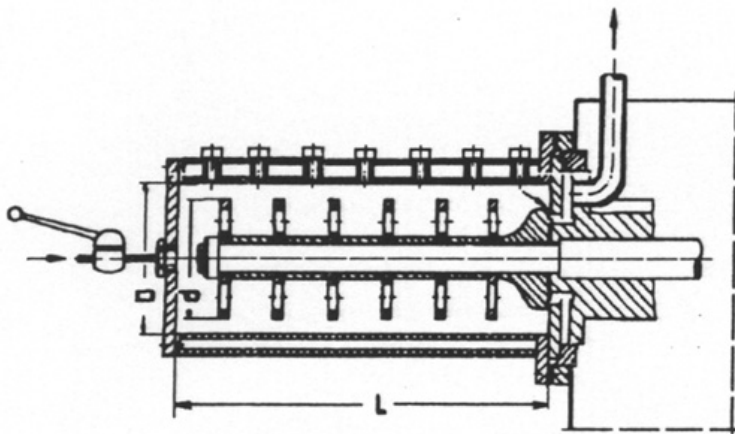


Lab-scale

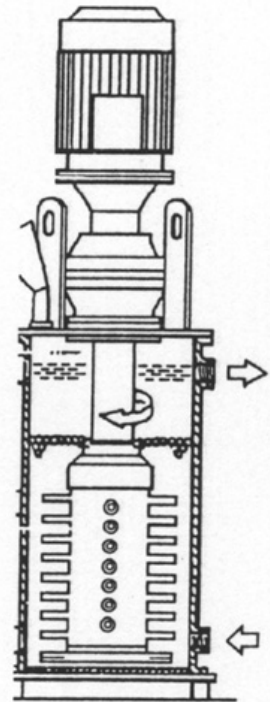


Full-scale

Figure 53



Horizontal stirred mill
(after Stehr et al 1983)



Vertical stirred mill -
Sala SAM mill
(after Wild et al 1993)

Figure 54

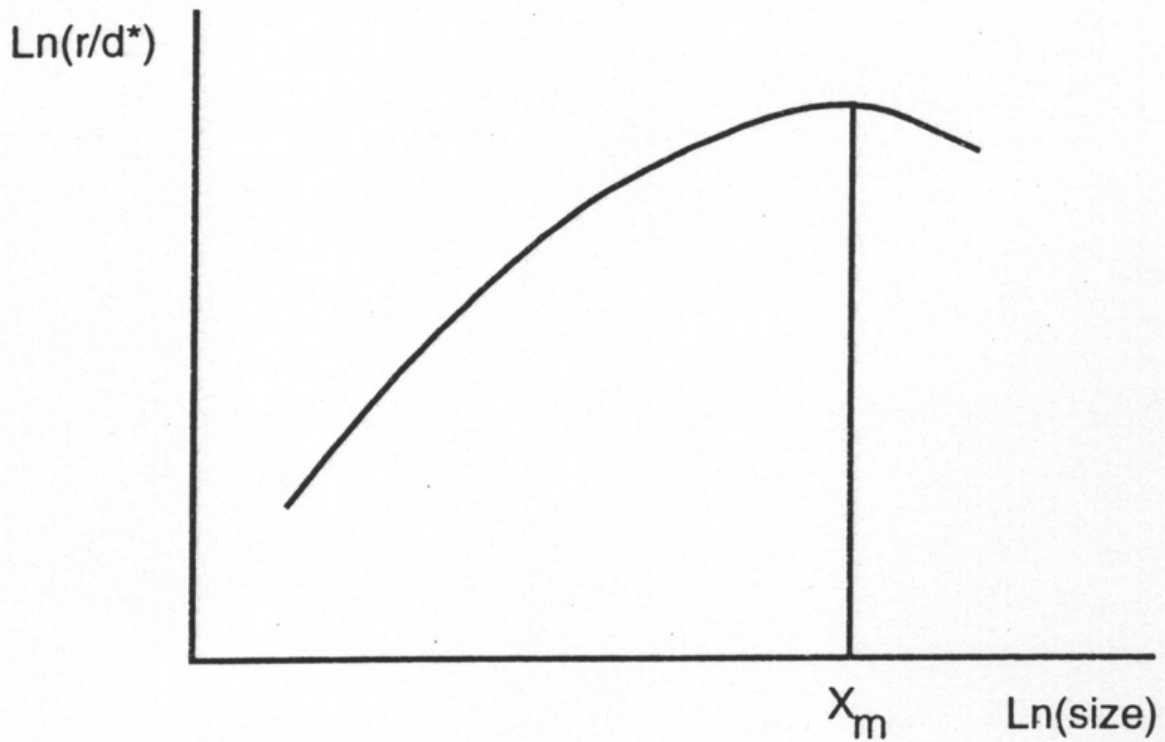


Figure 55

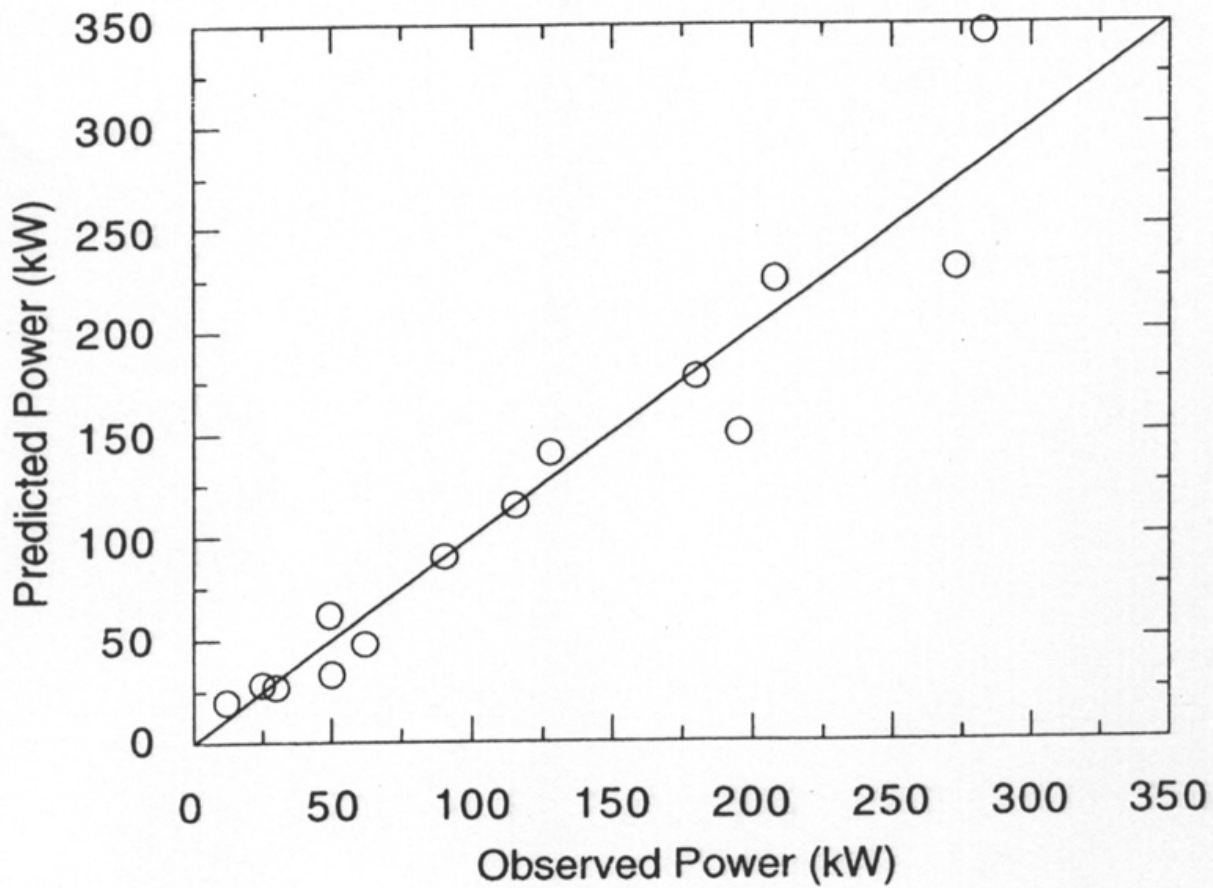


Figure 56

Breakage rate scale-up results

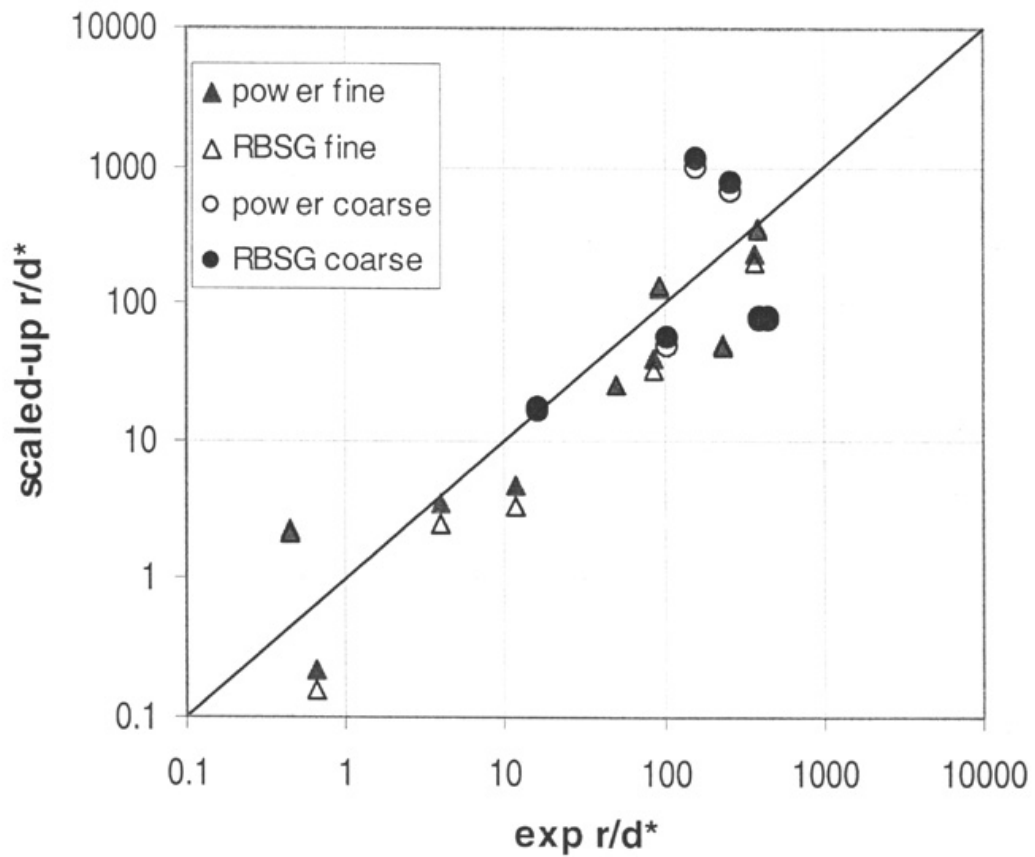


Figure 57

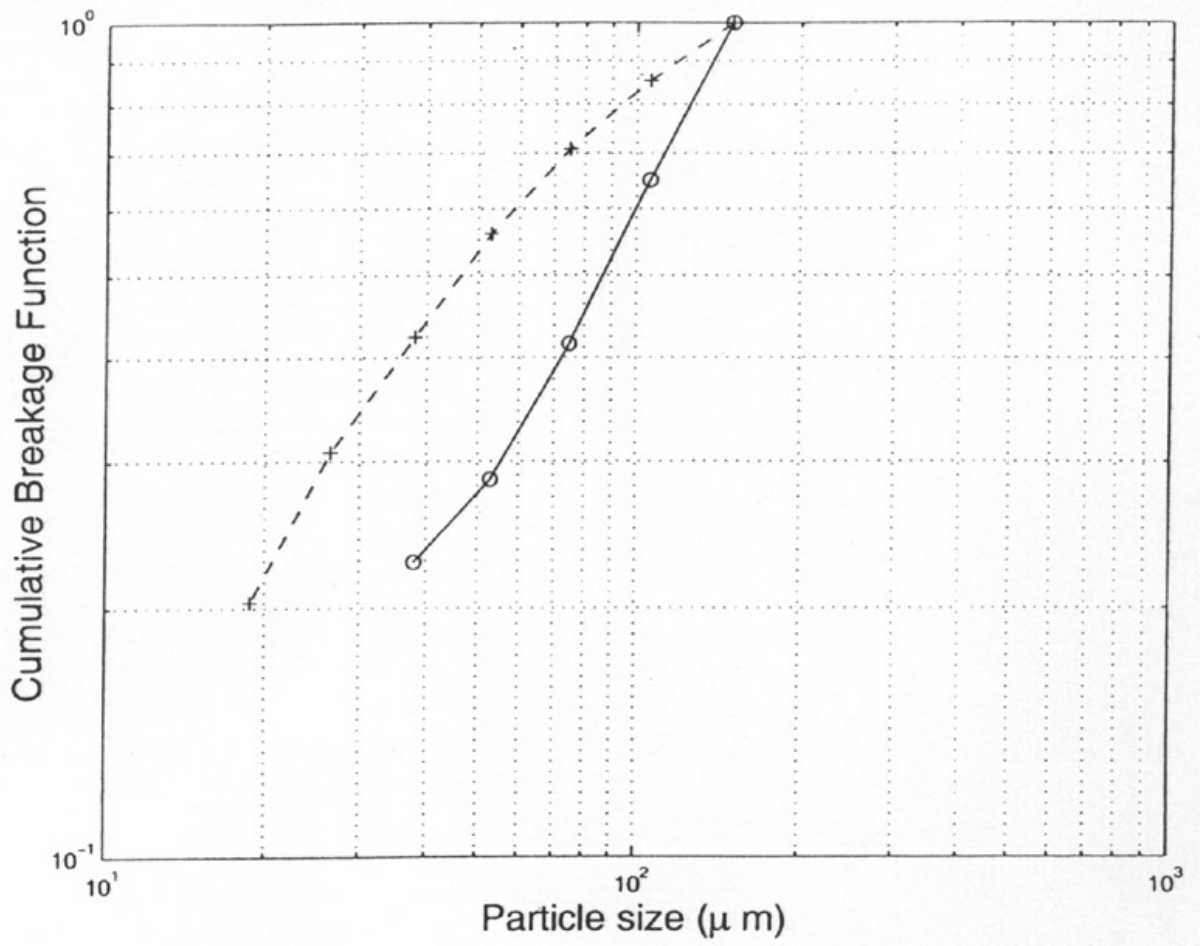


Figure 58

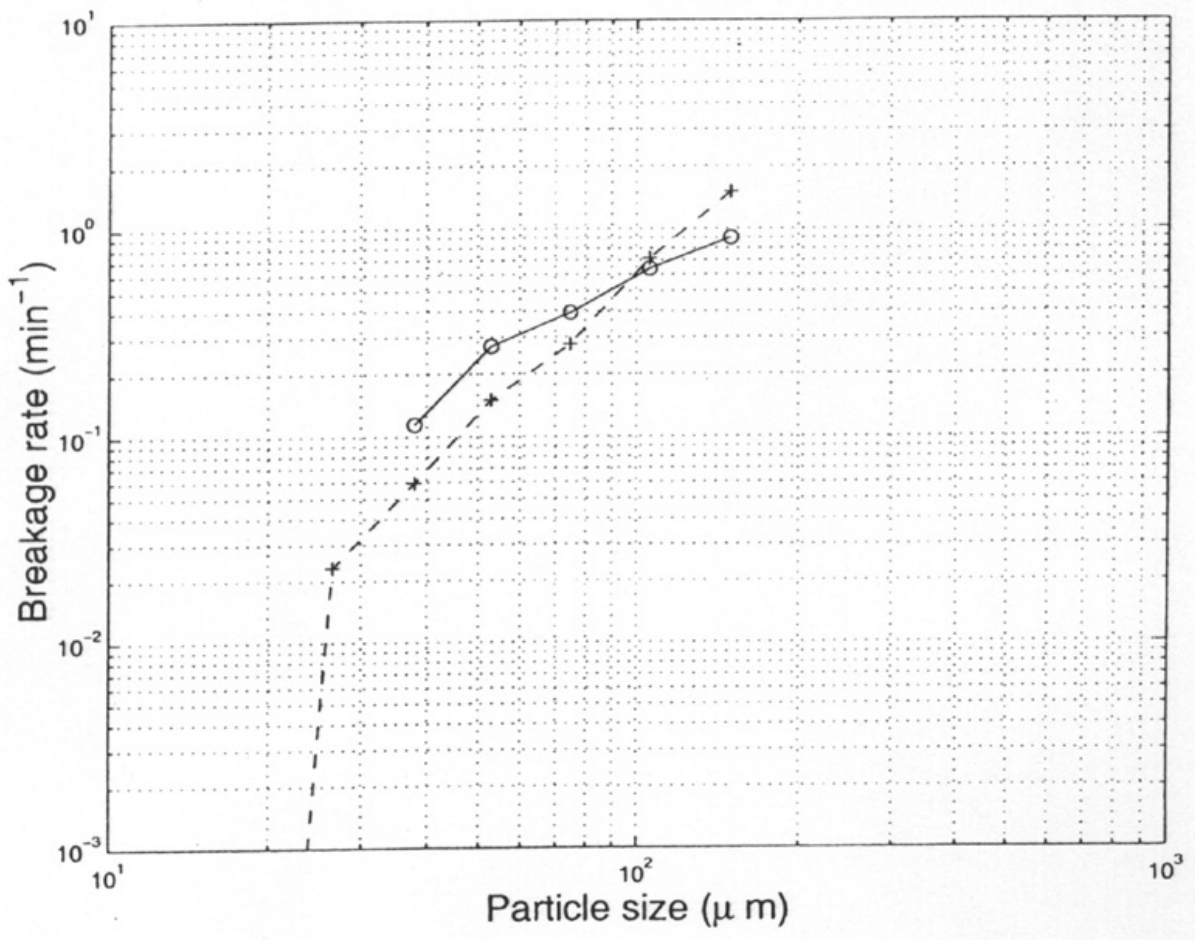


Figure 59

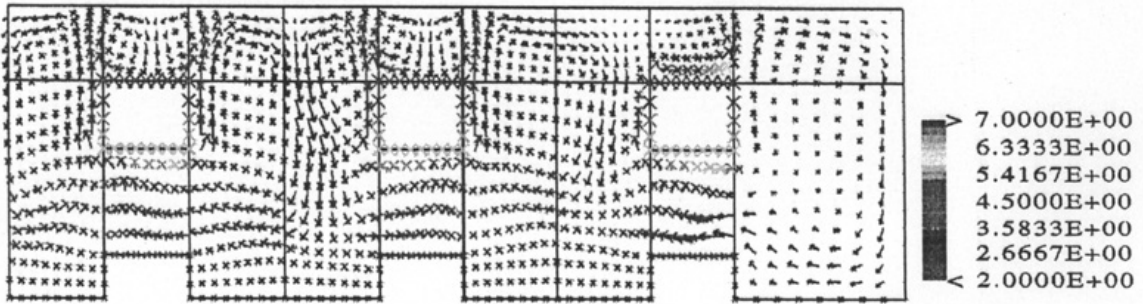


Figure 60

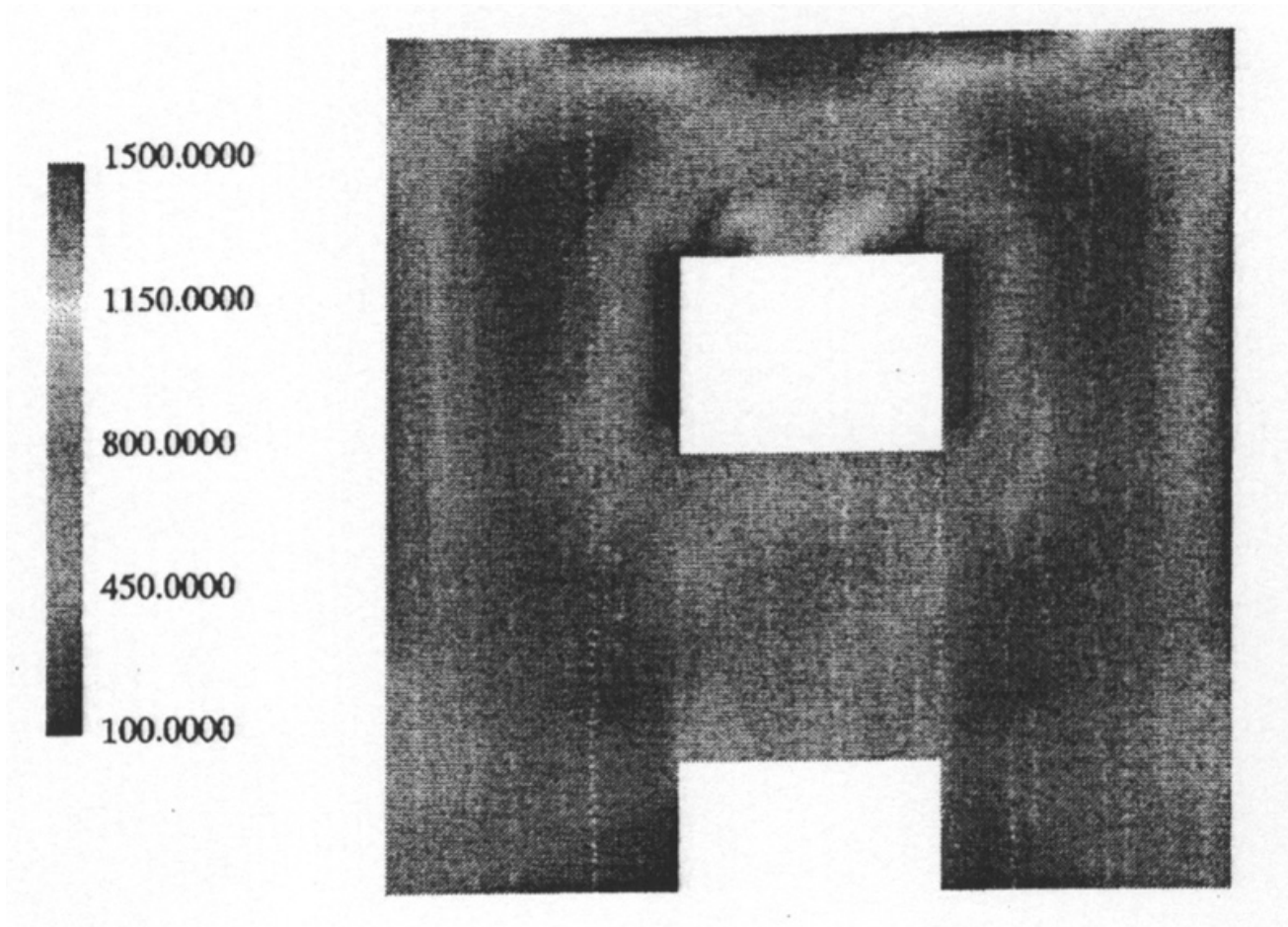


Figure 61

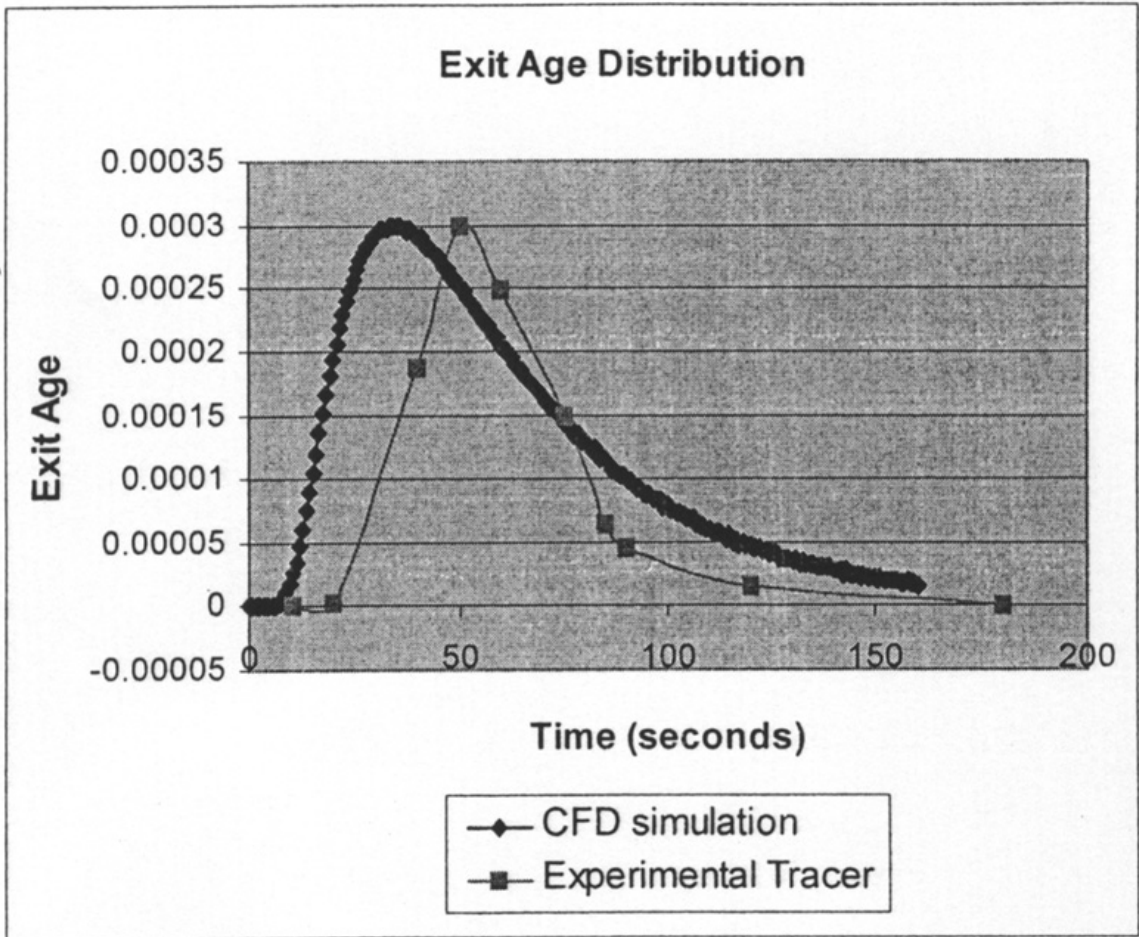


Figure 62

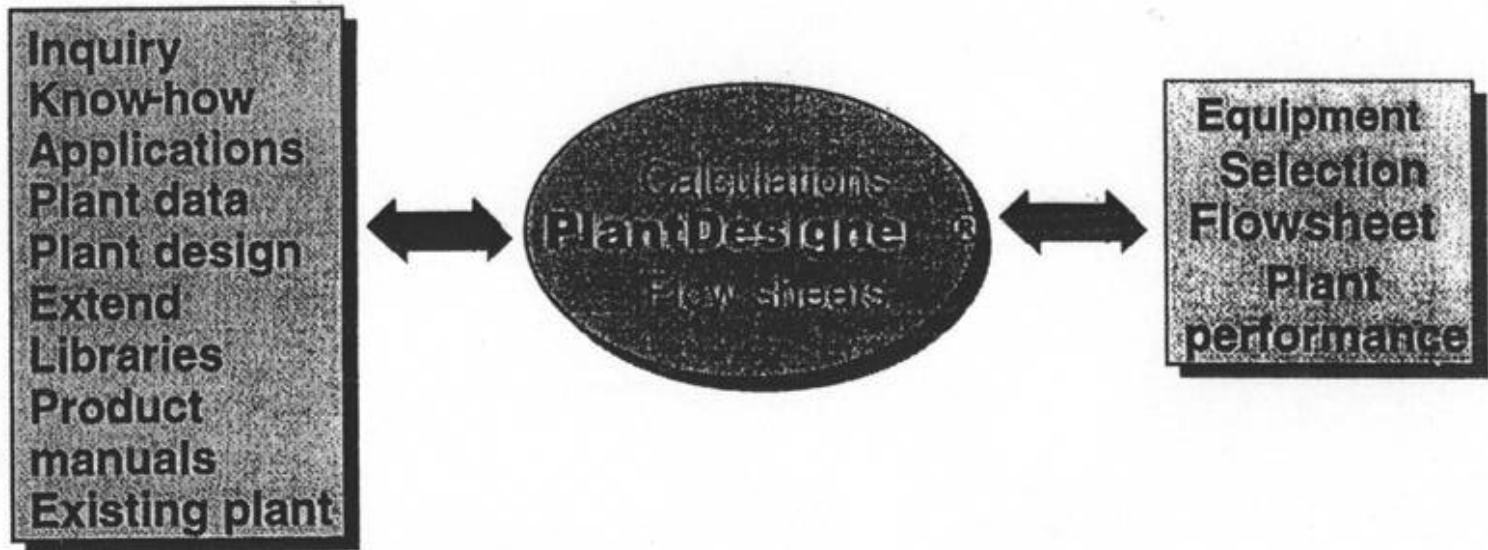


Figure 63

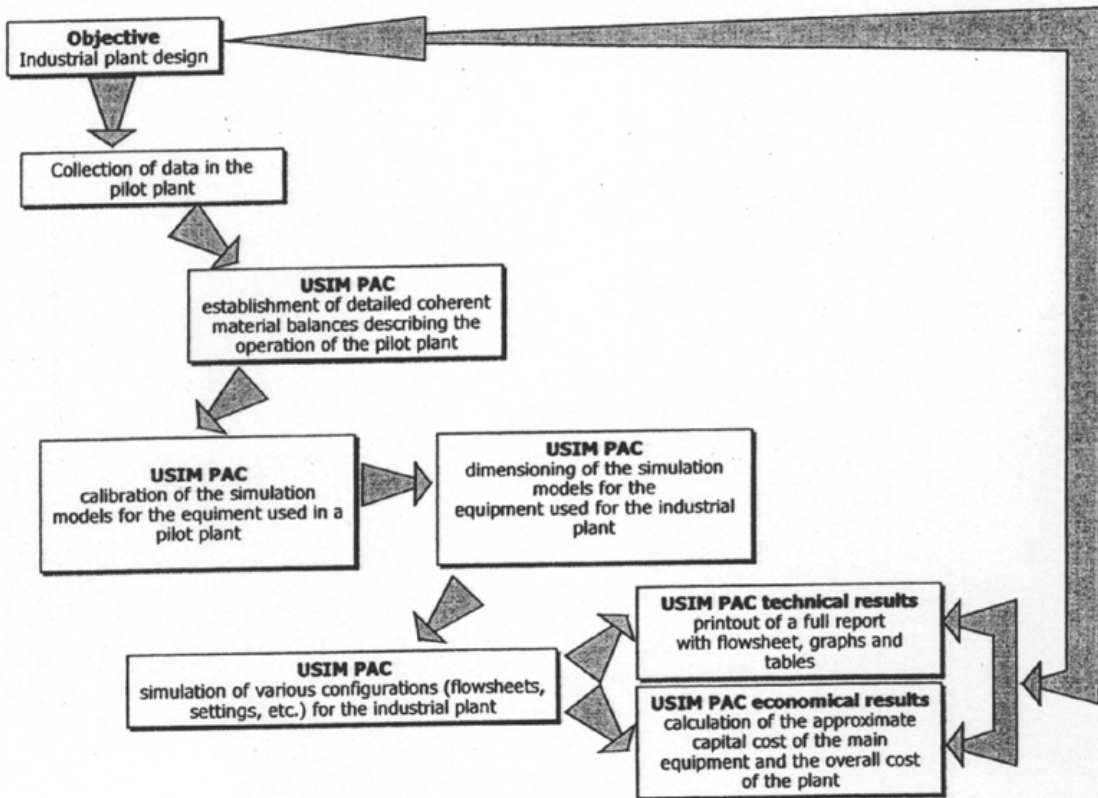


Figure 64

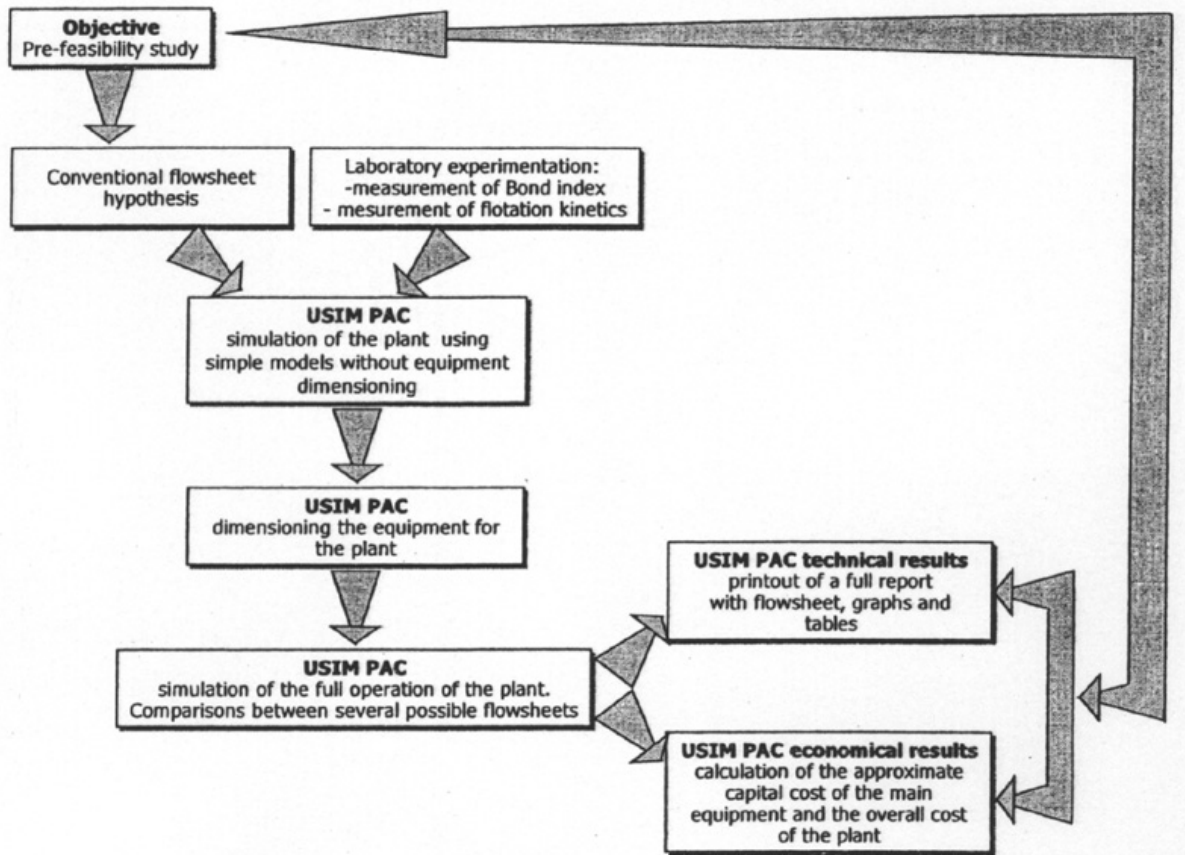


Figure 65

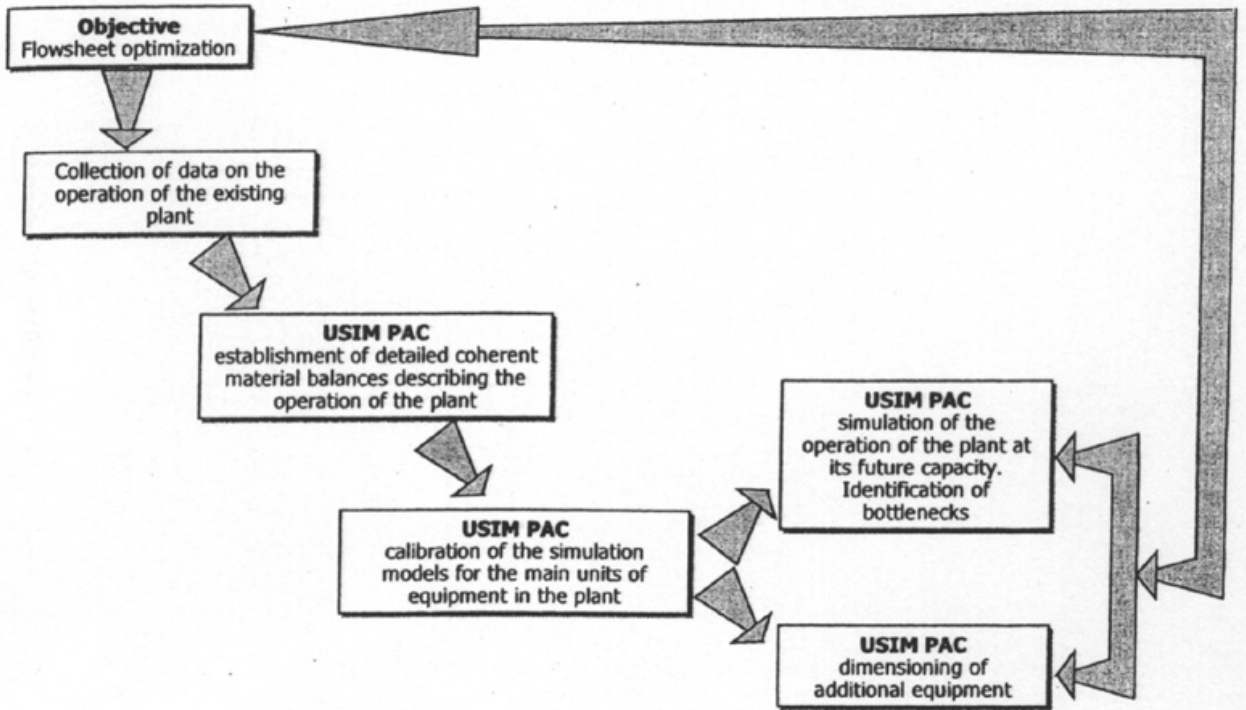


Figure 66

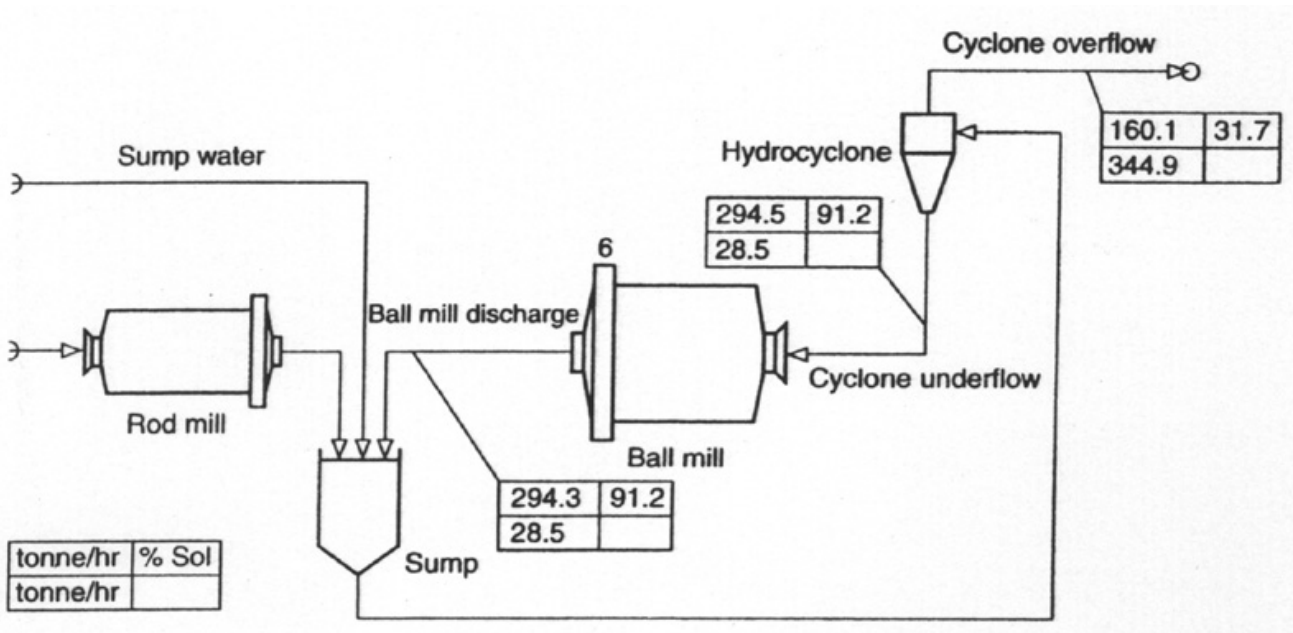


Figure 67

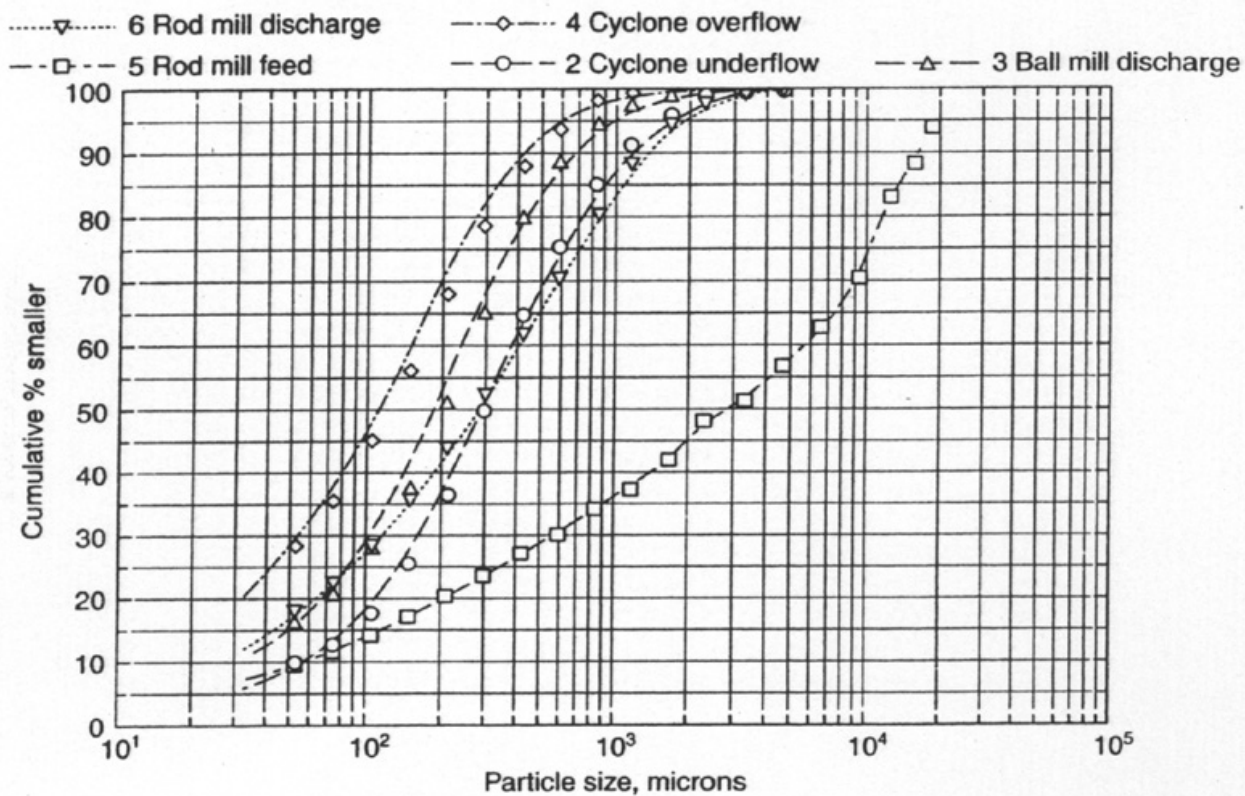


Figure 68

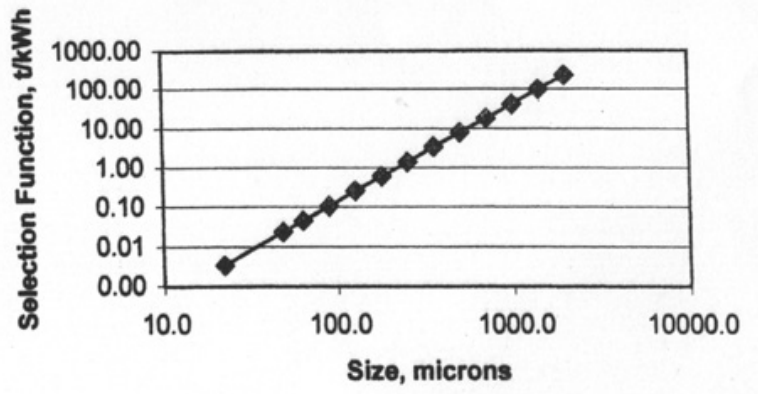
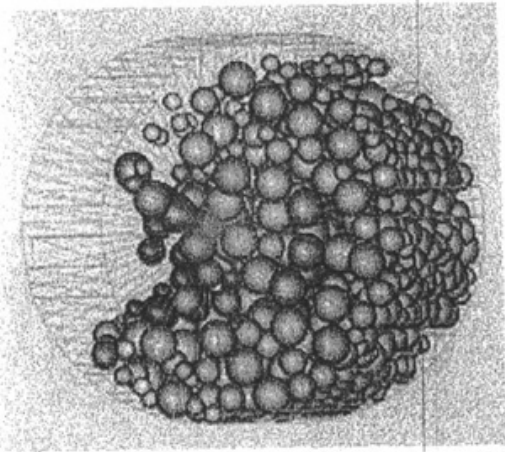
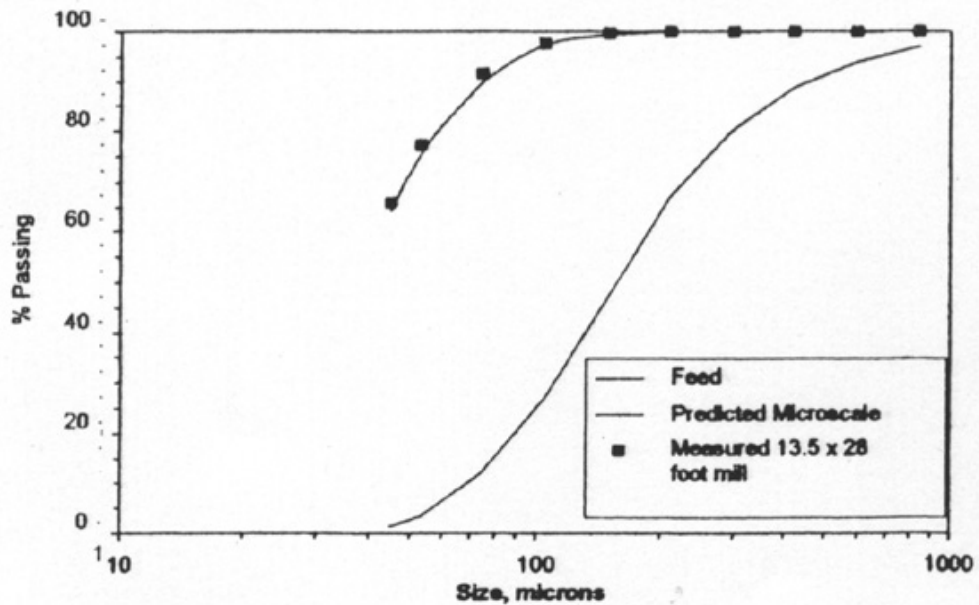
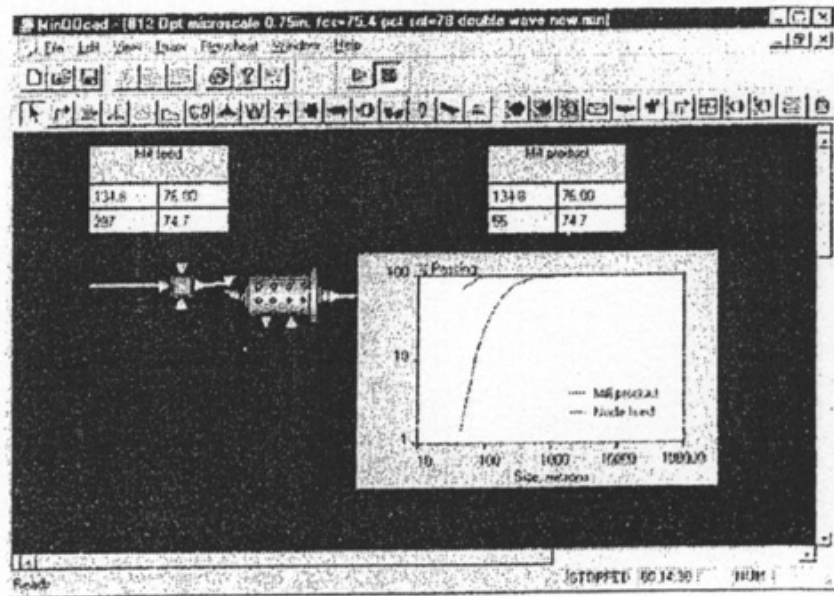


Figure 69



Picture 70